Princeton Plasma Physics Laboratory

PPPL-5201

A Short Informal History of TFTR Diagnostics

Kenneth M. Young

September 2015

Prepared for the U.S. Department of Energy under Contract DE-AC02-09CH11466.

Princeton Plasma Physics Laboratory
Report Disclaimers

Full Legal Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Trademark Disclaimer

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors.

PPPL Report Availability

Princeton Plasma Physics Laboratory:

http://www.pppl.gov/techreports.cfm

Office of Scientific and Technical Information (OSTI):

http://www.osti.gov/scitech/

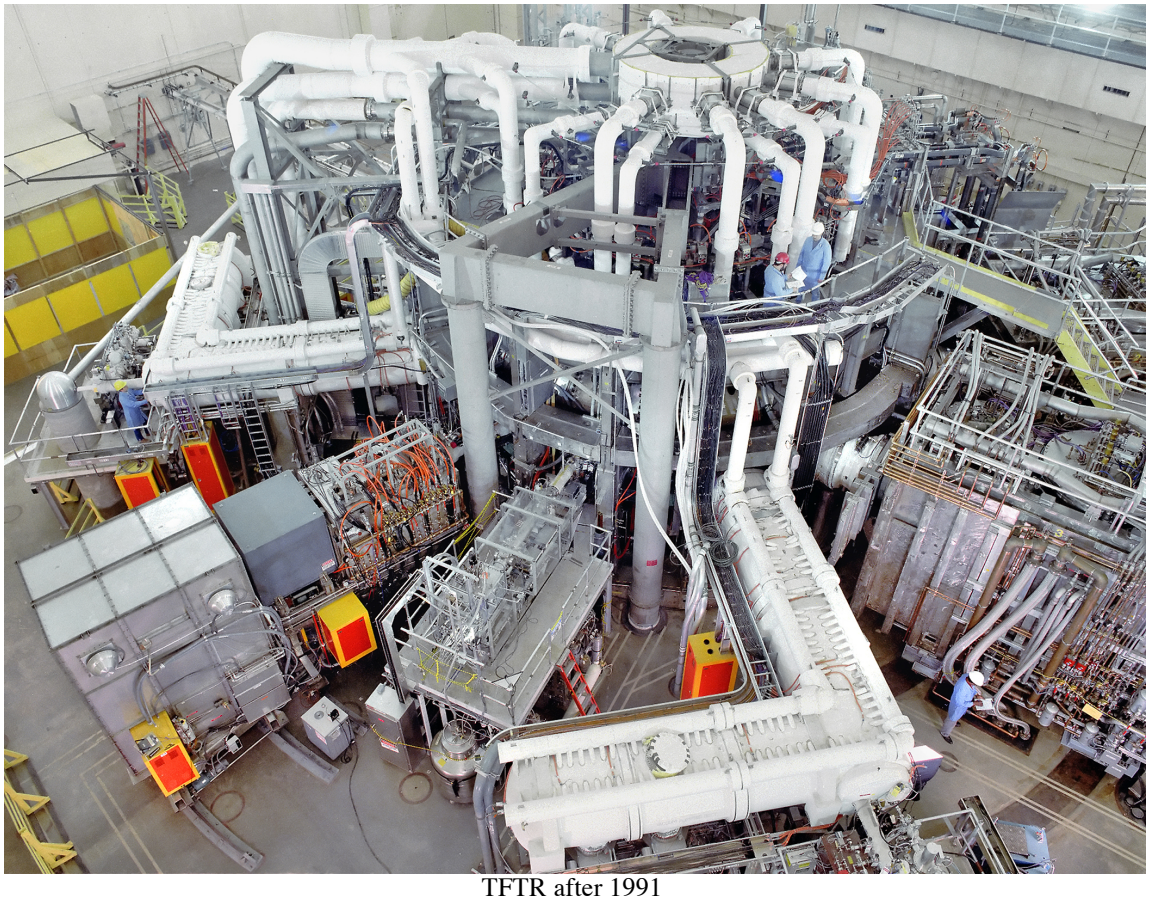
Related Links:

U.S. Department of Energy

U.S. Department of Energy Office of Science

U.S. Department of Energy Office of Fusion Energy Sciences

A Short Informal History
of
TFTR Diagnostics



TFTR after 1991

1975 – 1997

First D-T shot on TFTR: The image of a mask in front of a scintillator near TFTR illuminated by neutrons from the first D-T shot on December 9, 1993.

Introduction

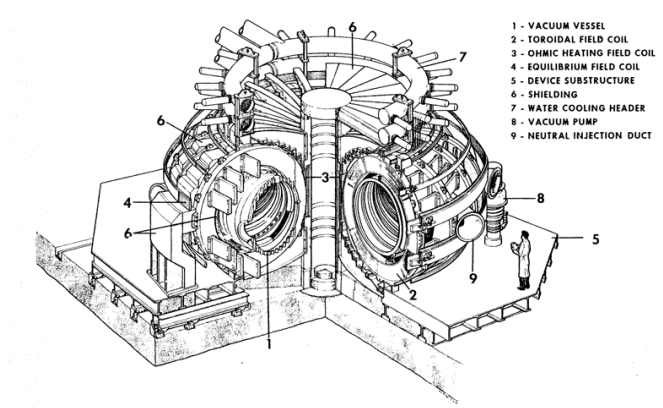
This short informal history is written from my perspective gained while leading the creation of the diagnostic systems for the Tokamak Fusion Test Reactor (TFTR). TFTR was a remarkable device and certainly had the best-diagnosed plasmas of any plasma device of the time. There were fortunate reasons for this high quality ranging from the culture of the Plasma Physics Laboratory (PPPL)[†] when it came to experimental measurements, to the excellent scientific and technical staff, to the configuration of the tokamak, to the support of DOE financially and to TFTR's timing with respect to the development of digital systems.

An important point to be aware of is that there were good reasons for the apparent plethora of diagnostic techniques applied to the measurement of a single plasma parameter in TFTR. Techniques have different temporal properties and different capabilities for spatial resolution. But more importantly, different techniques rely on different physics. In the early days it looked as though TFTR, with its relatively open access (at least before the introduction of tritium), would employ the peak instrumentation capacity to produce the best physics understanding. One could then anticipate a decline to the minimal set of instrumentation required for control of a burning plasma in a fusion reactor. However, with much physics exploration still to be done today, the success of ITER will depend on a huge array of diagnostic measurements.

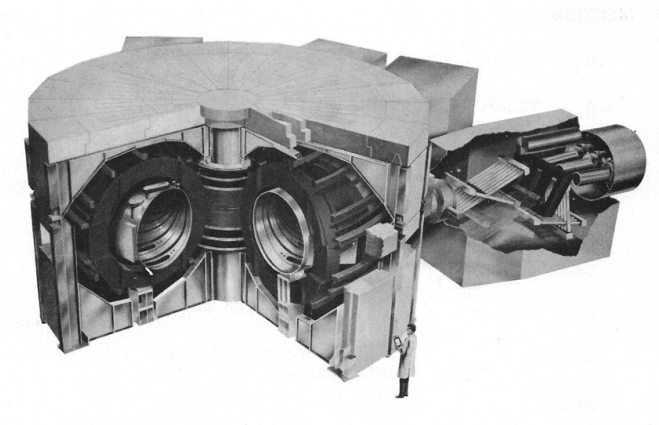
Kenneth M Young
July 2015

[†] At this time the name "Plasma Physics Laboratory" (PPL) did not include "Princeton" (PPPL). For simplicity PPPL will be used throughout.

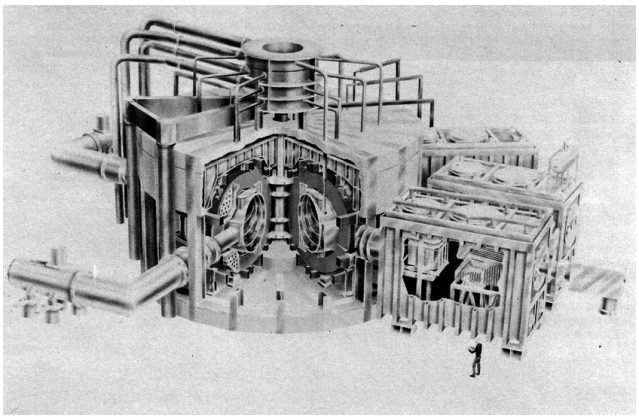
Concepts for TFTR



TFTR: Westinghouse Reference Design, November 1976.



TFTR: Ebasco-Grumman Final Design, August 1978.



TFTR: PPPL Information Bulletin, November 1982.

Westinghouse: The Early Days for Diagnostics

After approval of the TFTR project by Bob Hirsch, head of fusion research at DOE in July 1974, Westinghouse in Pittsburgh began the conceptual design of TFTR, then named the "two-component tokamak" (TCT) for its proposed use of high energy and power neutral beams, supplemented by adiabatic compression of the plasma, to create a large non-thermal ion population in the plasma to enhance fusion reactivity. This design work took place under the watchful eye of a small group at PPPL led by Paul Reardon. By early 1975, Harold Furth, then leading the Research Department at PPPL and supervising the overall project, became concerned about the cost structure of the device and particularly of the diagnostics. Of the $214M estimated for the project, only $2M was designated for diagnostics. Furth asked Kenneth Young to investigate whether this was sufficient. It turned out that the Westinghouse project head had over-ruled John Faulkner, responsible for diagnostics in the Westinghouse group, and had imposed this low number. However, it was not as ridiculous as some more recent low-balling of estimates for fusion devices. The background of the Westinghouse group was building fission reactors for which very simple instrumentation, with no requirement to support a scientific research program, could reasonably cost 1 percent of the total. Within about a month Young came up with a request for $35M, with little allowance having been made at that stage for developing alpha-particle diagnostics. Somehow, Furth managed to persuade Ken Moses at DOE and his superiors to provide this money in an operating fund, starting almost immediately. That was the start of a very encouraging relationship between PPPL and the DOE teams on site at PPPL and at DOE headquarters in Germantown, Maryland, which funded new and better diagnostics. Moses was succeeded by John Willis and later Steve Eckstrand. This increased funding benefited other PPPL devices, notably PLT and PDX, by enabling the hiring of new personnel and the setting up of laboratories for diagnostic development.

Apart from the lack of diagnostics, there were other problems with the facility that Westinghouse was designing. Initially there was no basement space under the tokamak, so diagnostic access to the bottom ports of the device was almost impossible. There was also practically no space for the electronic racks necessary to service the diagnostics. There was a building close to the test cell, which contained the tokamak itself, to house a control room, laboratories and physicists. There was no room for the test cell crane to pass over the tokamak. There was no underground connection to the main office building to join TFTR to the PPPL C-site. Jim French, the responsible engineer at Westinghouse (he later moved to Ebasco and PPPL) resolved most of these problems during this early design phase, with the laboratory building being integrated with the office building as a cost-saving measure.

One aspect in which Westinghouse excelled was in neutronics analyses. The company established very clear criteria for the shielding thicknesses required to meet the design goals for neutron emission. The design included a concrete "igloo" that closely surrounded the tokamak. This reduced the requirements for the thickness of the much larger external walls of the test cell, thus greatly reducing the construction cost. Eventually, the igloo proved to be unnecessary because TFTR's operational program evolved to be quite different from the original plan, and also because much more equipment (which also provided some measure of shielding) was installed in the test cell than Westinghouse had been told to anticipate.

A Growing Program: Ebasco and Grumman

A consortium of Ebasco Services, a major construction company in the nuclear industry, and Grumman Aircraft, which was coming off its highly successful Apollo Lunar Module (LEM) fabrication, was awarded the design and construction contract for TFTR in late 1974. Giffels, Inc. won a contract from DOE to design a new PPPL facility to become known as D-site to house TFTR, and an addition to the C-site facilities, originally built in the 1960s for the C-stellarator. There was a major integration of the teams, managed by Paul Reardon. Ken Wakefield led the PPPL engineering oversight and early on set up a configuration control system which ensured review of any changes being proposed by different parts of the overall design team. Sam Goldfarb led the engineering design for the diagnostics; he provided conceptual design drawings for all the diagnostics, so defining access requirements to the tokamak and space for the equipment throughout the TFTR area.

Initially, Grumman played a big role in the scientific parts of the project. It provided considerable design support for the diagnostic concepts but gradually, as more PPPL staff became involved, the company's contribution to diagnostic development faded. One interesting aspect of the involvement with Grumman was that the company had an effective summer program for children, a number of whom spent time at the Laboratory working on the diagnostics. Ebasco did provide design support for many of the larger diagnostic installations to supplement the PPPL engineering manpower, and also provided support in the PPPL drawing office for a number of years.

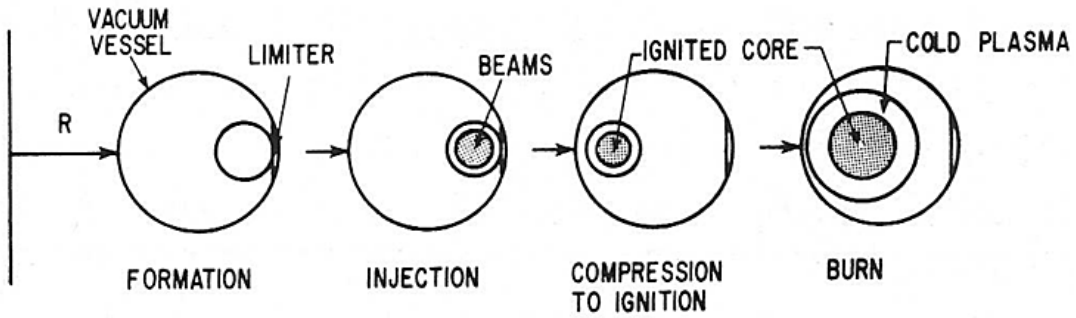
Terminal Construction Corporation was the low bidder for putting up the buildings and was awarded the contract. Since the designs of very few diagnostics (or other ancillary equipment) had progressed beyond the preliminary stage at the time of this contract award, a lot of assumptions had been made on penetrations through the thick concrete of the test cell and basement walls, and through the floor, based on the conceptual designs. While these assumptions were reasonable, given the state of knowledge at that time, a number of costly changes became necessary during the construction of the overall facility.

TFTR Groundbreaking – October 1977; Mel Gottlieb, Bill Bowen, Paul Reardon, Lyman Spitzer, DOE Assistant Secretary Robert Thorne, and Len Reichle (Ebasco).

D and C construction sites in 1978.

Influence of the Program Plan on Diagnostics

The original program plan that there would be a total of only 4,000 full-power shots had a dramatic effect on diagnostic planning. The additional concept of achieving the highest D-T performance by major radial compression of the plasma (part of the TCT concept) also had a significant impact on ideas for diagnostics and hence on the tokamak port design. In particular, spatial information about the plasma parameters had to be gathered in a single shot, a major departure from the prevailing practice of building up profile data shot by shot. The relatively large size (plasma radius ~ 1m) and long pulse length (pulse duration ≥ 1 sec) of TFTR made meeting this goal reasonably easy.

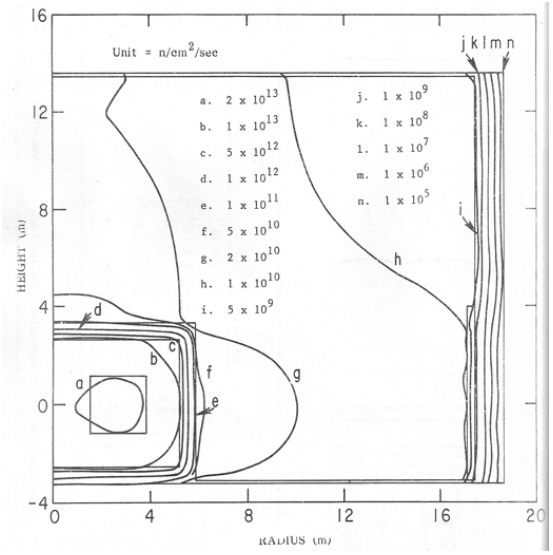


An idealized picture of achieving a burning plasma through compressing the plasma in major radius.

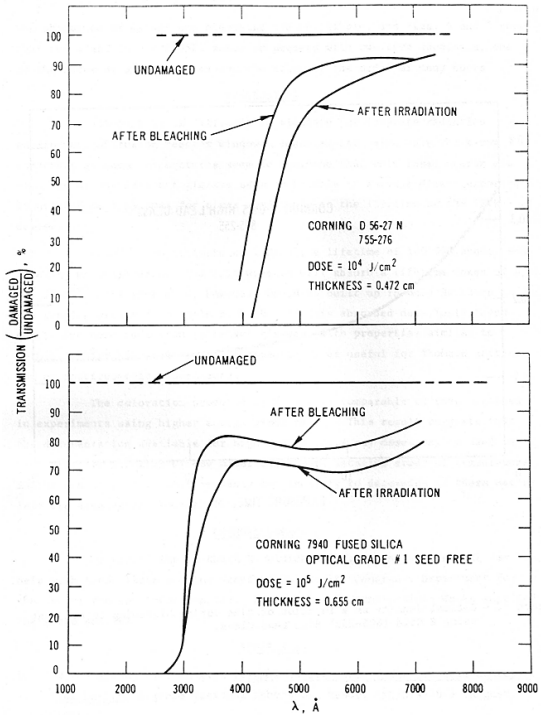
Funding for the diagnostics was sought and obtained annually at the same time as funding for all the other components of the TFTR budget. Hence there was tight coupling between the program planning and the diagnostics necessary for carrying that program out. Since the diagnostics took more than one year to complete, judgment on how to handle the flow of funds for each system was always necessary.

For the diagnostics that involved new measurement concepts, funding was needed for development, fabrication and installation on the tokamak. It often took a long time for an installed instrument to operate reliably and routinely provide data into the TFTR database. It generally took about five years for all the steps from concept to reliable operation, even with the closely integrated operation at PPPL.

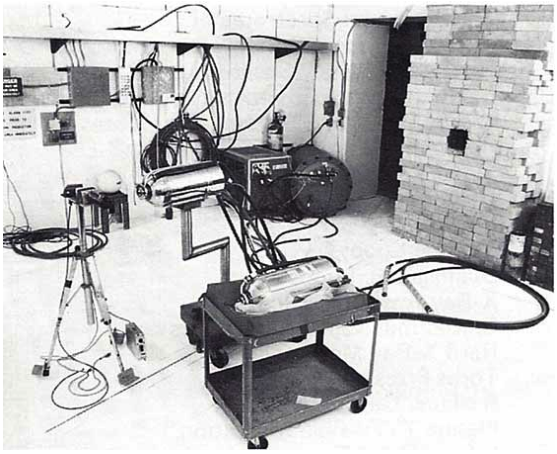
Then there were new challenges to face because of the presence of tritium and the neutrons it would lead to. Elastomer vacuum seals could not be used, so new hard window-seals had to be developed for some special windows. All windows had to pass pressure-cycling tests before installation on the tokamak. Pressure gauges had to be tested for their sensitivity to the electrons emitted by tritium atoms. Insulators were carefully chosen for the in-vessel components, and the potential need to shield systems that would be in the test cell with the tokamak was in every designer's mind. Penetrations through any of the floors and walls of the building needed special care to prevent neutrons from streaming out during experiments, and to maintain the required air-pressure differentials on each side of the penetrations.



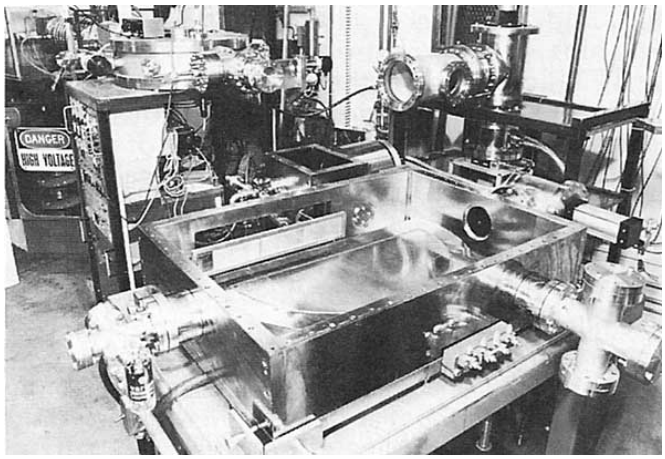
1980 neutronics modeling of the neutron fluxes surrounding TFTR (with its igloo shielding) (Ku, PPPL 1711 (1980)).



Results of exposing two of the possible window materials at LAMPF. Fused silica was chosen (Norem & Young, ANL TM 79 (1977)).



The neutron test facility in early 1981 showing the two Kaman accelerator heads for 2.5 MeV and 14 MeV neutrons (FY'81 PPPL Annual, fig. 69).



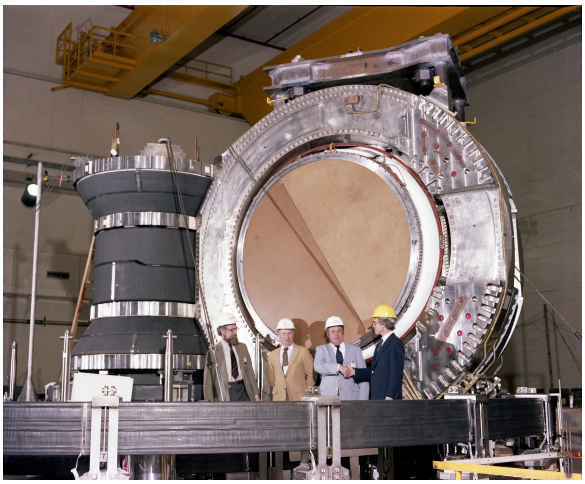
A prototype neutral particle analyzer in the calibration laboratory (TFTR 35 (1980)).

PPPL Management and TFTR Diagnostics

TFTR Diagnostics benefited enormously from the culture of the laboratory, developed over many years. The culture required that every possible aspect of the plasma had to be measured, preferably with more than one technique, to be understood and related to predictions. The directors of the laboratory, Gottlieb, Furth and Davidson, all encouraged and backed the necessary funding. J.R. Thompson, who was briefly deputy director, was highly supportive in organizing engineering support. In the construction phase, Reardon was also highly supportive, though he did remove some funds very early on for more critical procurements for the tokamak. When Don Grove took over for final installation of the tokamak and during its early operational years, he brought with him his experiences from the PLT and ST tokamaks and the C-stellarator, and kept diagnostics as a high priority. Dale Meade, both in his role as Grove's deputy and when he took over the TFTR management, was a huge advocate and took a lot of interest in the development of the novel diagnostics being considered for D-T operation. As TFTR headed towards D-T, Rich Hawryluk maintained the strong position of support, though he had to balance diagnostic support against the enormous demands of completing the tritium system and obtaining regulatory approval for D-T operation.

In addition to the strong funding support of the DOE team in Germantown, the staff in the local DOE office under Don Carden and Milt Johnson provided constant backing.

1981: The TFTR Test Cell prior to the tokamak installation (81E1297).



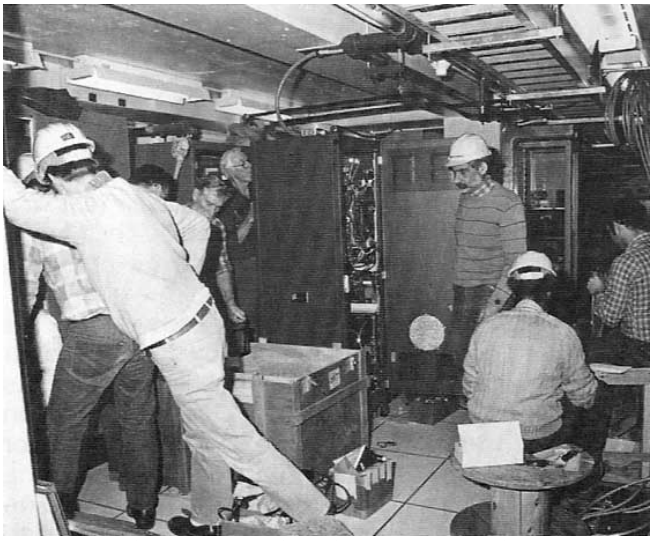
May 1982 - Installation of the first TF coil for TFTR: Harold Furth, Don Grove, Paul Reardon and Milt Johnson (DOE Area Office).

Preparation of the TFTR Site for Diagnostics

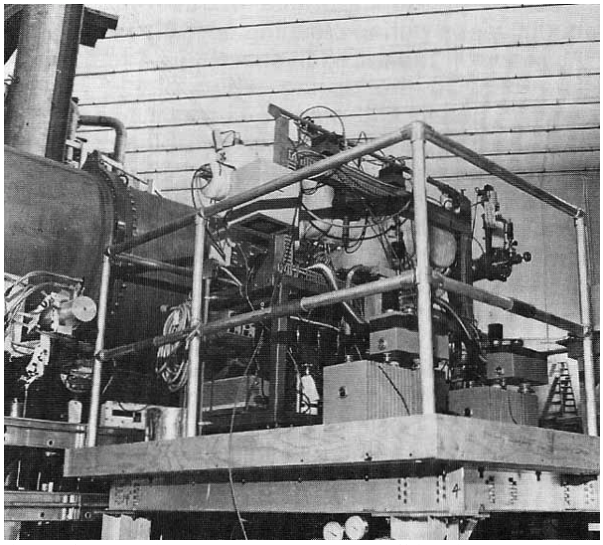
In the neighborhood of a tokamak, most of the infrastructure that has to be installed in the early days is that required by the diagnostics. Services such as electrical power, vacuum connections, and compressed air are all essential. For TFTR, electrical installation was a major challenge and a team from SAIC (Oak Ridge) led by Gil Zigler and Jim Gulizio was brought in to provide the design effort. They implemented the critical single-point ground concept and the necessary isolation transformers and cable-routing system to ensure clean diagnostic signals. Design and installation of AC power for the TFTR test cell, as well as for the basement and data acquisition rooms, was provided by this team. Although the design for the cabling necessary for first plasma had long been completed, the Ebasco wiring installers had not gotten around to doing any of the work by Friday, December 17, 1982, and claimed no possibility of completing the work by the end of the year. At the planning meeting that Friday, Young took the work away from Ebasco and asked Jack Joyce, then head of PPPL Engineering, to take on the job. A PPPL team, led by Art Wise. started on the Saturday and finished the necessary installation by Tuesday, in good time for first plasma. It turned out that, according to a ruling by Herb Mix of DOE, the diagnostics belonged in a research category and its installation was not covered by the Davis-Bacon Act requiring union labor.

For first plasma on December 24, 1982, compressed air for operating diagnostic valves was provided from a cylinder and the vacuum pumps were simply vented into the test cell. The compressed air system was installed in 1983 and the vacuum system integration into a common effluent through the tritium-handling system was also started that year.

Installation of diagnostics and other ancillary equipment went on for all the years of TFTR's life. All sorts of other installations went on in parallel, very often by subcontracted labor. Since the normal electrical code applicable to industrial installations requires comprehensive and often redundant grounding, there was a constant need for removing ground loops which would lead to contaminated diagnostic signals. Hence a ground-fault monitor was installed that sounded loud alarms when it detected additional grounds. The monitor was normally turned off during installation periods to avoid constant alarms as workers created inadvertent loops with tools and while connecting cables. A team of "ground-busters" under Jim Taylor spent many very early morning hours cleaning up the errant grounds to enable trouble-free operation by 8 a.m. This team's overtime hours became an issue for upper management but never for the diagnosticians, who had extraordinarily noise-free signals.



Myron Norris and the engineering team preparing the data acquisition room (DARM) on December 21, 1982 (82E1190).



One of the residual gas analyzers (RGAs) installed for first plasma (82E1176).

The Digital Revolution

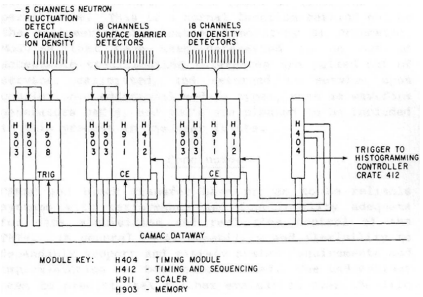
The initial purpose of the tunnel between the D-site and the Laboratory Office Building (now the Lyman Spitzer Office Building) in which the TFTR control room and main computers were located, was to carry a multitude of cables for analog signals between the tokamak systems and the Central Instrumentation, Control and Data Acquisition (CICADA) computers. Structures for holding tiers of cable trays on either side of the tunnel are still visible. Fortunately, despite opposition from management because of the perceived added cost, the tunnel had been made wide enough to allow a person to move equipment out to D-site.

In a short time it became apparent that the optimum solution for data and control signal transmission would be to convert signals from analog to digital in the data acquisition rooms (DARMs) in the TFTR basement and to transmit the data digitally, by much more secure and noise-free fiberoptics. Suitable signal-processing electronics conforming to the CAMAC standards then in use were coming onto the market. But to meet the unique TFTR diagnostic demands many new modules had to be developed at PPPL by the Computer Division under Bob Daniels and Joe Bosco. A very distinct advantage of the overall data transmission scheme was the electrical isolation between components at the two ends which had different grounding environments. In the end, the tunnel wall only carried a small set of data-transmitting fiberoptic cables, a few copper cables for the hardwired interlock system, a cable carrying emergency power to the control room, and the plastic piping of the neutron activation diagnostic.

As the physics needs on TFTR expanded, the need for data storage capability grew enormously. Initially 35 Mbytes of data storage per shot was grudgingly agreed to by the CICADA team when it specified its computer system. At the end of TFTR's life, diagnostic front ends included personal computers each equipped with hundreds of times more memory capacity.

One consequence of the large number of diagnostics on TFTR was the large number of people, both PPPL employees and collaborators, required in the control room for the two daily shifts, especially the evening shift. Hence, in about 1990, the management pioneered the ability to view data and control diagnostics (but not the tokamak itself which remained isolated from the wider world) from a remote desk (e.g. home or office), which greatly reduced the experimentalists' need to be in the control room and, hence, their stress level.

Apple II Computer, c1980 (Web picture).



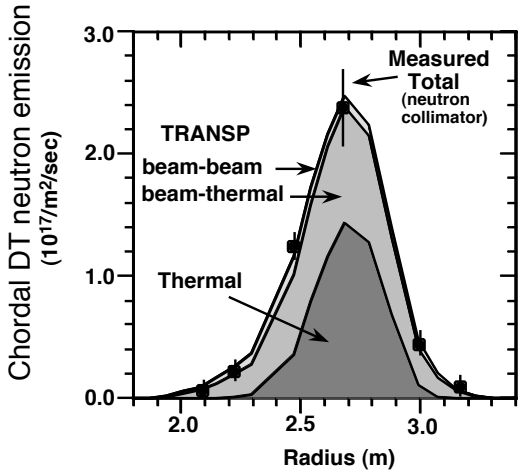
Schematic for the CAMAC crate for some neutron diagnostics (Rauch et al., IEEE Trans. Nucl. Sci., **34**, 970 (1987).

Communicating for data analysis between PPPL and U. Wisconsin.

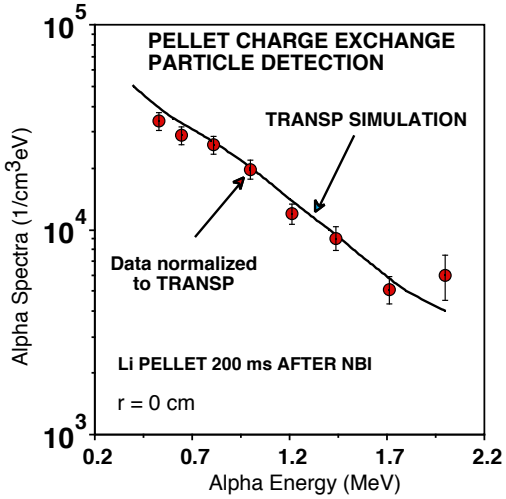
The TFTR main control room early in 1980 (804835).

SNAP and TRANSP

The value of the diagnostic data for the operation of the TFTR tokamak, the execution of experiments and the understanding of the plasma behavior were enormously enhanced by the capability for immediate between-shot, or next-day, analyses. For most diagnostics, the raw data was analyzed immediately after each shot and fed into the one-dimensional, time-independent, kinetic transport computer code, SNAP, developed by Jane Murphy and others, to provide between shots a picture of the plasma behavior at various "times-of-interest" to guide the operation. Data from a few shots, perhaps with some additional analysis by diagnostic operators, would be analyzed overnight by the full time-dependent transport code, TRANSP, developed by Doug McCune and colleagues. These codes, which evolved considerably during the life of TFTR, gave an initially unique and always invaluable advantage over experiments being operated elsewhere that lacked the comprehensive and integrated TFTR diagnostic and data-handling capabilities.



A TRANSP fit to spatial neutron emission data for a D-T supershot in 1994 (McGuire et al., APS 13195 (1994)).



Comparison of an observed confined α-particle energy spectrum with TRANSP modeling of the discharge in 1994 (McGuire et al., APS 13195 (1994)).

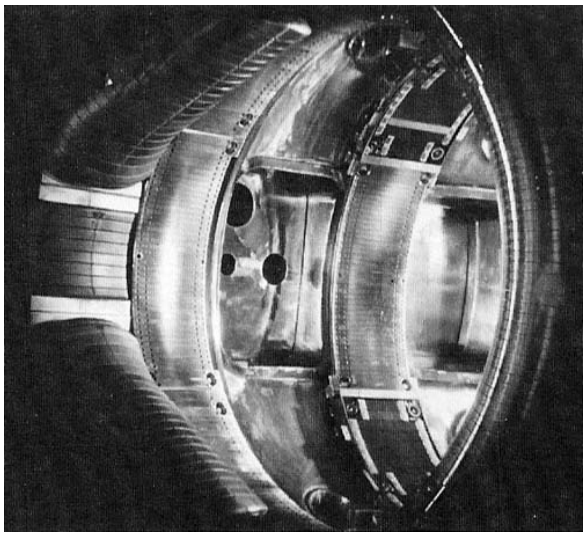
Description of Diagnostic Progress, Year-by-year

In reporting the diagnostic readiness in each year, it must be clear that much effort had already gone into preparing those systems for successful operation in the year they are mentioned. It should also be understood that no diagnostic stayed unchanged from its first installation through the life of TFTR. Each diagnostic may have been introduced in a simple form, (e.g. with one single observation channel or with only slow electronics) but it was always enhanced as need was demonstrated or as funding and technology allowed. Since installations of one kind or another went on in maintenance weeks or down-periods for most years of TFTR's operation, only the successful demonstrations of diagnostic operation are identified by year in what follows.

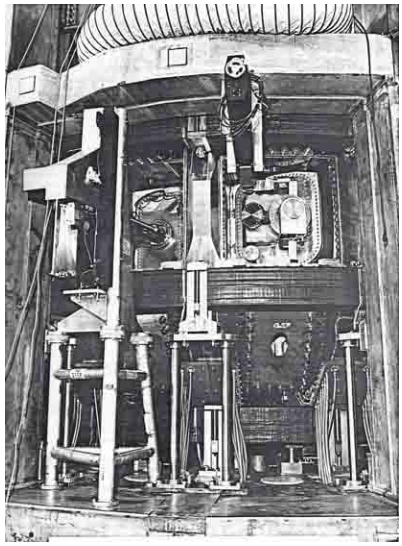
One big advantage of TFTR being operated at PPPL was that prototypes of the diagnostics could be checked out on PLT or PBX-M, where the engineering implementation could be relatively fast and access was more readily available.

TFTR as a pre-eminent tokamak producing fusion-relevant plasmas with excellent basic diagnostics, attracted many excellent physicists to share in its successes. The science produced in TFTR was quite extraordinary. It attracted very high quality staff to work at PPPL and also attracted a host of collaborators from other institutions. All the PPPL personnel who were listed as authors of papers about the diagnostics program are listed in Appendix 1. The collaborators participating in the diagnostic work named as authors for major publications on the diagnostics are shown in Appendix 2.

3.06 a.m. December 24, 1982 – First TFTR plasma – Nelson Grace (DOE), Harold Furth, Don Grove, Bob Woolley and others in the remote control room.

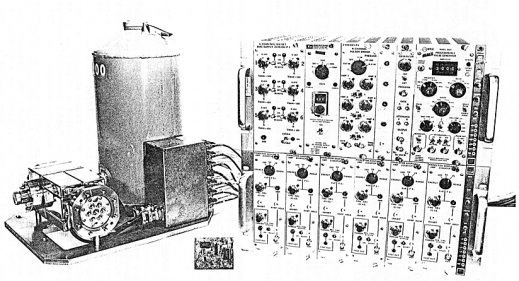


The limiter "jaws" in TFTR in 1983 as viewed by one of the periscopes using the in-vessel lighting (FY84 PPPL Annual, fig. 24).



The electron-beam probe for measuring magnetic fields in the vacuum vessel (TFTR 48 (1982)).

Two Mirnov coils at the bottom of the vacuum vessel (93E0464).



Silicon and germanium detector array with its signal-processing electronics for the x-ray pulse height analyzer (TFTR 43 (1982)).

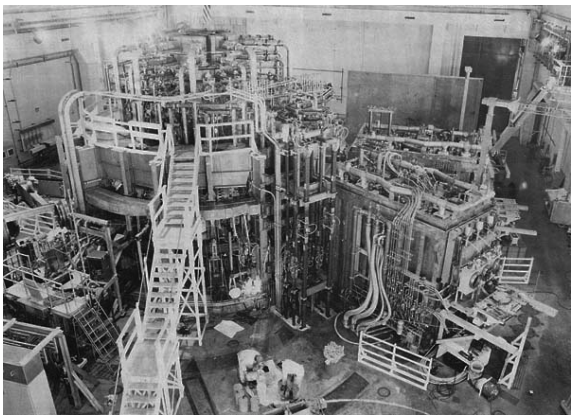
Fiscal Year 1983

This was the year of the first TFTR plasma early in the morning of December 24, 1982. The plasma current was only 51kA, the current channel appeared to be quite narrow, and the discharge lasted barely 50 ms.

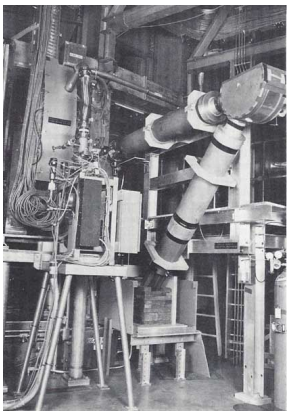
A rather frugal set of diagnostics was all that was available and needed for the first plasma. The first of John Coonrod's magnetic loops for determining the plasma current and its position, Fred Dylla's vacuum gauges and residual gas analyzers, and Phil Efthimion's 1-mm microwave interferometer for the line-integrated density all registered data. But the first clear evidence of the successful production of a plasma came from John Lowrance's plasma TV system observing the interior of the vacuum vessel through its modified submarine periscope.

In the first three months of 1983, huge progress was made with adding additional diagnostic systems. Inside the vacuum vessel, Mirnov magnetic loops were installed on the wall to allow study of unstable MHD activity in the plasma. John Schivell installed the first-ever radiation-hard bolometer detectors of radiation from the plasma. These bolometers were in arrays to give spatial information about the radiation. Electron temperatures could be measured with a heterodyne radiometer in the microwave region (Phil Efthimion) and a pulse height analyzer working in the x-ray spectral region (Ken Hill). Ion temperatures could be sampled by a neutral particle analyzer (Sid Medley) and the first of the neutron detectors, the epithermal fission chambers (Ernie Nieschmidt). The first measurements of impurities in the plasma were made with an interference filter array and a survey spectrometer in the ultraviolet range, both brought on line by Alan Ramsey. Diamagnetic loops for measuring the plasma pressure were added outside the bellow sections of the vacuum vessel by Coonrod. Lists of the diagnostics applied in that first year of operation are shown in tables 1 and 2.

In the next run period in 1983, with additional power supplies installed and feedback control implemented, plasma currents of 800 kA could be held constant for over 1 s in deuterium plasmas, with energy confinement times up to ~ 190 ms inferred from the diagnostics.



TFTR in 1983 (84E0691).



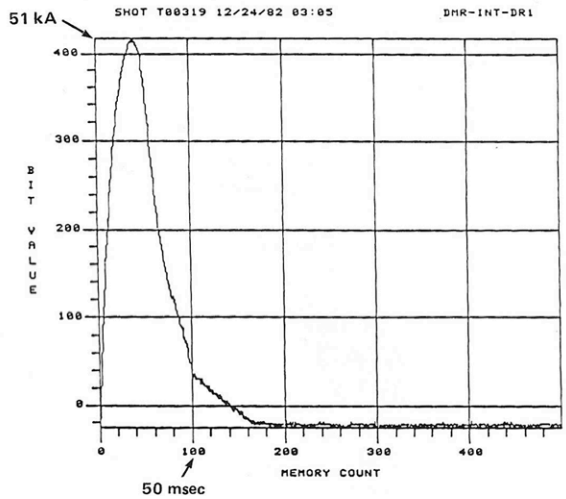
X-ray imaging system (left) and first x-ray crystal installation in 1983 (83E1247).

Table 1: Diagnostics for First Plasma

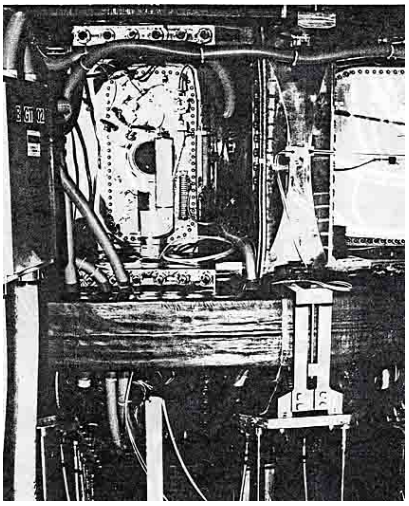
Diagnostic	Parameter being Investigated
Rogowski loops	Plasma current
B_θ/B_p loops, saddle coils	Plasma position
Voltage loops	Voltage around torus
I mm microwave interferometer	Plasma density
Hard x-ray monitors	Runaway electrons
Torus pressure gauges	Neutral gas pressure
Residual gas analyzers	Vacuum quality
Plasma TV, illumination	Fast TV pictures of the plasma
Glow discharge cleaning probes	Conditioning of vacuum vessel
Electron beam alignment probe	Quality of toroidal magnetic field

Table 2. Diagnostics for Ohmic-heated Plasmas

Diagnostic	Parameter being Investigated
Mirnov loops (inside vacuum vessel)	MHD instabilities
Diamagnetic loops	Plasma pressure
Fast-scanning heterodyne radiometer	Electron temperature
X-ray pulse height analyzer	Electron temperature and impurities
Neutral particle analyzer	Ion temperature
Ultraviolet survey spectrometer	Impurity levels
H_α-interference filter array	H_α-light, bremsstrahlung radiation
Wide-angle bolometer	Total radiation levels
Bolometer array	Spatial distribution of radiation
Epithermal neutron detectors	Neutrons from limiter, ion temperature
Infra-red TV temperature monitor	Heating of limiter surfaces



The current in the first TFTR plasma (84X2330).


Moveable head of one optical periscope (TFTR 41 (1983)).

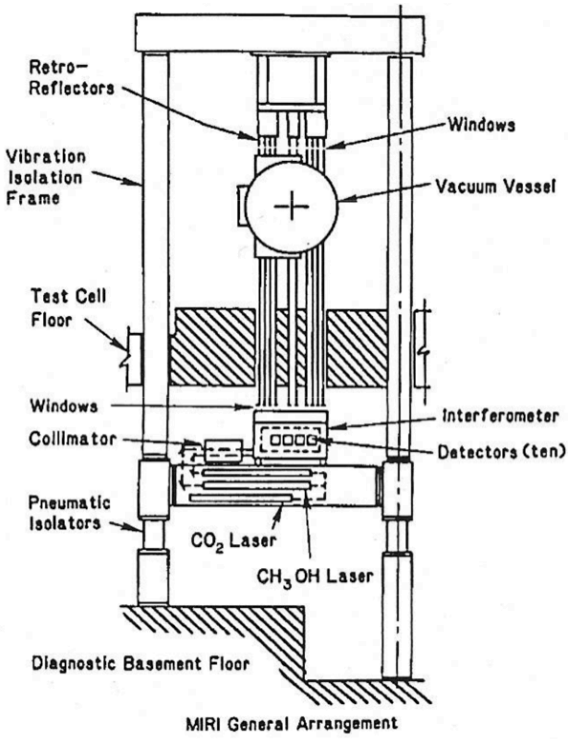
Fiscal Year 1984

This was a year of major improvements in the performance of ohmically-heated plasmas and engineering installations. The year culminated with the installation of the first auxiliary heating — two neutral beams that became available at the end of the year. The first protective armor was installed inside the vacuum vessel. Bakeout of the vacuum vessel at 150°C and pulsed discharge cleaning to condition the plasma-facing walls enabled better plasma performance. The tokamak could routinely operate with toroidal fields at 4.0 T and discharges with plasma currents of 1.4 MA lasting up to 4 s were routine. The first attempts at compressing the plasma in major radius were begun.

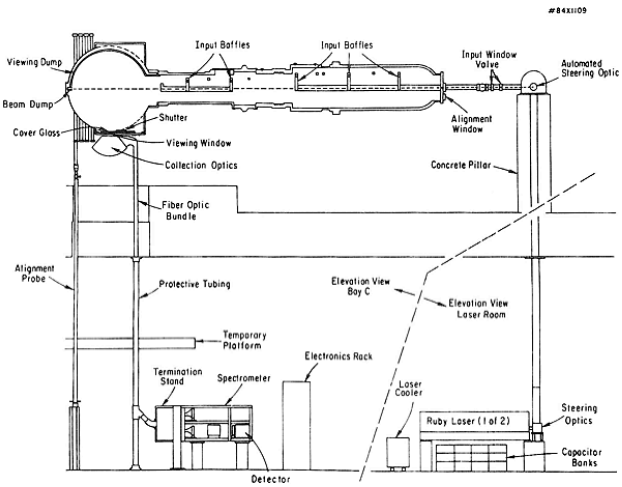
For measurement, there was a huge advance with the addition of new diagnostics and additional capability in terms of additional channels and upgraded electronics for those already in place. The electron density profile could be measured, although initially rather coarsely, by Dennis Mansfield's multichannel far-infrared interferometer with only five operational channels. It could also be measured at a single instant of time by the TV Thomson scattering system of Dirck Dimock and Dave Johnson. This device also gave spatial information on the electron temperature, whose measurement was also enhanced by Gary Taylor's fast-scanning heterodyne radiometer and the Fourier transform spectrometer of Fred Stauffer from the University of Maryland. Another chord was added to the neutral particle analyzer for ion temperature measurement, but the bigger gain in capability for diagnosing the ions came through installing the first Bragg x-ray crystal spectrometer by Manfred Bitter and two multichannel visible spectrometers by Alan Ramsey. The understanding of the behavior of impurity ions was helped by the addition of an ultraviolet survey spectrometer (SPRED) by Brent Stratton and a soft x-ray spectrometer by Szymon Suckewer based on a design developed by an Israeli, Jean-Louis Schwob. Plasma fluctuations, already seen with the Mirnov loops, could now be studied with a 64-chord x-ray imaging system (which could also be used for temperature measurement) from Ken Hill and Kevin McGuire. Bill Heidbrink began to measure fluctuations in the neutron emission using plastic scintillators, but most of the effort for the instruments to measure fusion-products lay in getting them installed. Dennis Manos installed the first probes, with a variety of configurations of their tips, for measuring properties in the plasma edge.

Some practical improvements were made for the operation of the machine. Ken Hill had five hard x-ray monitors installed on the test cell walls. Infrared pyrometers for limiting the neutral-beam heat load on the vacuum vessel wall were installed by Sid Medley. Probes carrying lamps were added so that the plasma TV system could be used for inspection of the inside of the vacuum vessel without breaking the vacuum. This system was also improved with infrared capability so that it could monitor the temperature of the limiter and inside wall during a plasma pulse. Glow discharge cleaning was enabled, with probes being installed. An injector of impurities for study of transport in the plasma was provided by Sam Cohen.

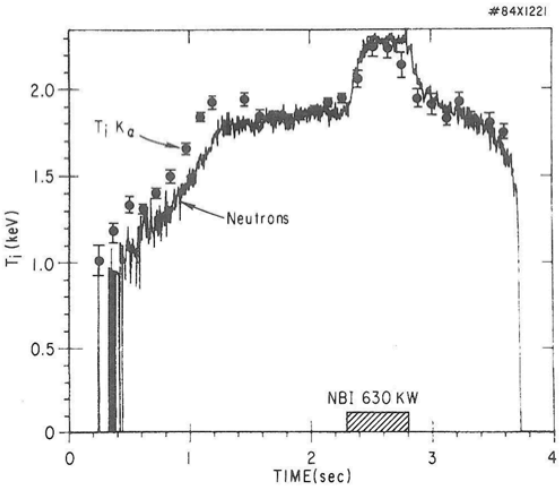
A photograph of the outer two legs of the vibration-isolated tripod stand for the multichannel interferometer (MIRI) (Mansfield, Appl. Optics, **26**, 4469 (1987)).



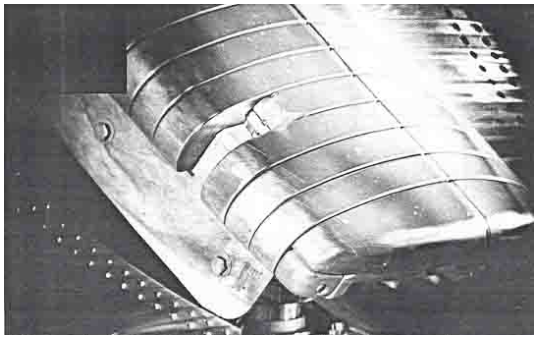
Drawing showing the MIRI general arrangement relative to the tokamak vacuum vessel (Mansfield, Appl. Optics, **26**, 4469 (1987)).



Layout of the Thomson scattering system with the laser and detectors in the basement and the input beam traveling through one of TFTR's pumping ducts (84X1109).



Ion temperature evolution as detected with neutrons and Doppler broadening of the TiXXI K_α spectral line (84X1221).



Missing piece of limiter detected using the external inspection periscope (TFTR 55 (1984)).

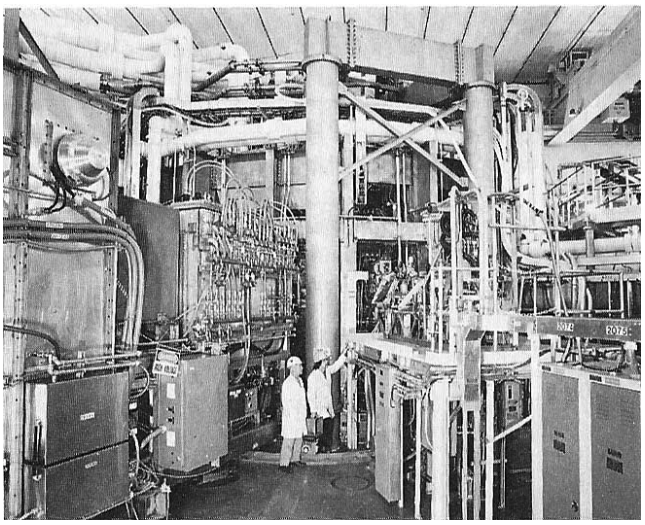
Fiscal Year 1985

The big progress in physics experiments this year was made possible by the two neutral beams which delivered up to 6 MW of power at ~ 80 kV to the plasma, and also by a repeating pellet injector from ORNL. This injector could provide a single 4 mm diameter deuterium pellet, or multiple 2.7 mm pellets, for fuelling with speeds of ~ 1300 ms^{-1}. The tokamak also reached its design goals of plasma currents of 2.5 MA at a toroidal field of 5.2 T. The internal wall protection, called the inner bumper limiter, was upgraded to a set of graphite tiles backed by water-cooled Inconel, and a set of zirconium aluminum surface-pumping panels was installed.

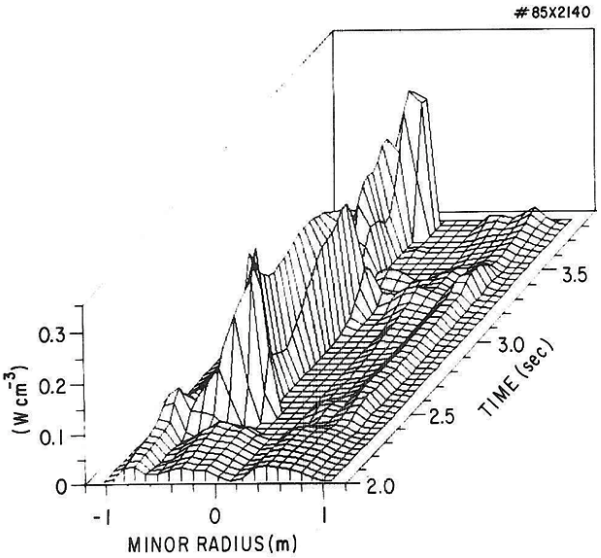
The physics advances lay mostly in extending the range of operation with ohmic plasmas at higher plasma currents and in the first studies of plasmas heated by neutral beams. With the neutral beam heating, the energy confinement was quite disappointing, with the L(low)-mode confinement being observed. The study of adiabatic compression of the plasma, the original scheme of operation for TFTR, was de-emphasized because of disappointing improvements in performance and difficulties in maintaining electrical isolation of the tokamak structure during the high-voltage pulses applied to the poloidal field coils to compress the plasma.

Most of the work on diagnostics was directed at significant upgrading in FY 1986. The electron density profile measurement was improved, with 10 channels of the interferometer operational and Thomson scattering being able to pulse twice in a discharge. For electron temperature and impurity identification Ken Hill added two channels of x-ray pulse-height analysis, viewing upwards from the basement. Sid Medley and Lane Roquemore added two more viewing sightlines for neutral particle analyzers, one of them vertical for the ion temperature. The greater advances in measuring the ion temperature and flow velocity arose with the introduction of three views, two vertical and one tangential, of charge exchange recombination spectroscopy (CHERS) by Ray Fonck, and three new vertical views of x-ray crystal spectroscopy by Manfred Bitter. These x-ray channels, aiming slightly off-vertical, also provided information about the toroidal flow of the plasma. John Schivell added two tangential bolometer arrays viewing in opposite directions to provide better understanding of the power radiated from the plasma.

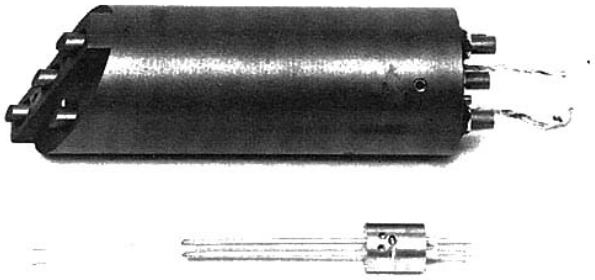
The increased power being introduced into the plasma brought the planned set of fusion-product diagnostics into action. An array of four proton detectors installed inside the vacuum vessel by Jim Strachan began to take data. The neutron activation system, with eight locations on the outside of the tokamak with its pellet loader and gamma-analyzers in the basement of the Lab Office Building beside the control room, began operation under Ernie Nieschmidt. The first channel of the neutron collimator in its shielded housing in the basement was brought on line by Hans Hendel. It was also necessary to introduce the use of Campbelling and count modes into the electronics for the epithermal neutron detectors to handle the increasing yield of neutrons from the plasma. Bill Heidbrink added four more plastic scintillators on the outside of the vacuum vessel for measuring fluctuations in the neutron emission.



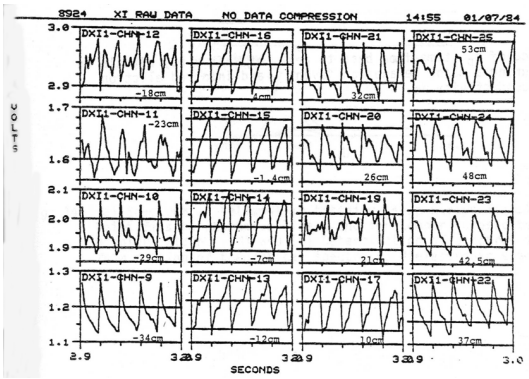
The diagnostic neutral beam is shown on the left (85E1507).



Localized edge radiation measured by a bolometer array (85X2140).



3-pin Langmuir-calorimeter probe head (above) for the edge plasma of TFTR compared to a core plasma double Langmuir probe head for the C-stellarator (84E0780).



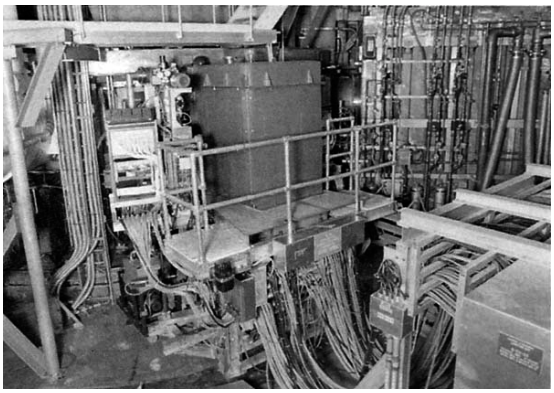
Sawteeth MHD fluctuations observed by channels in the x-ray imaging system (TFTR 52 (1983)).

Fiscal Year 1986

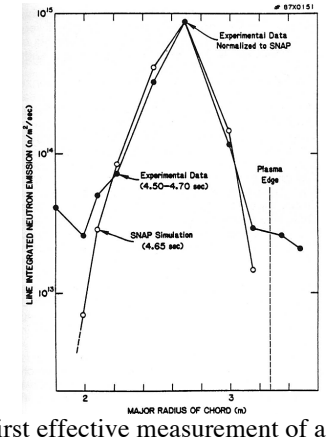
Plasma performance was very much better in this year with the discovery of TFTR "supershots" produced by new wall-conditioning techniques and increased neutral beam power of up to 15 MW. The plasma confinement reached about three times the value consistently obtained in the ohmic plasmas in L-mode confinement. These supershots produced record ion temperatures of up to 17 keV. Neutron yields from D-D reactions over 1 x 10^{16} n/s significantly affected noise on the diagnostic signals. Now the motor generator sets and energy conversion systems were regularly operating at their design values. With these advances in operation and heating, a proposal to add ~10 MW of ion cyclotron power to the tokamak was approved. Unfortunately, this good progress in science was not reflected in the DOE fusion budget, whose reduction led to the first lay-offs of staff from TFTR. These largely affected subcontractors and did not much affect diagnostics. But they did cause a delay in the start of the D-T program.

Dennis Mansfield and Hyeon Park upgraded the multichannel infrared interferometer to provide better spatial definition of the density profile. They began to test out the measurement of the Faraday rotation of the beams as a way of determining the density of the current in the plasma. A grating polychromator in the microwave spectral region giving twenty spatial channels was introduced by Al Cavallo and Mike McCarthy, with the instrument located in the basement outside the shield wall. This instrument had the advantage for measuring the electron temperature of being very sensitive to fluctuations and able to replace the data of the x-ray imaging system that became degraded at higher D-D neutron yields. The horizontal x-ray pulse height analyzer was moved outside the test cell wall, again to increase capability during later D-D operation (and obviously D-T). Two vertical channels were placed in the basement. The CHERS system was improved with opposing tangential sightlines for the ion temperature and rotational velocity profile of the plasma. Another spatial channel was added to the vertical x-ray spectrometer since the detector for the horizontal system had been disabled by the neutrons during the best deuterium pulses. A major addition was that of a diagnostic neutral beam (DNB) installed by Gerd Schilling, which operated this year at up to 54 keV, well below its 80 keV rating, for about 200 ms. This enhanced the charge-exchange fluxes by a factor of five or so. A near-UV spatial scanning spectrometer was added by Alan Ramsey.

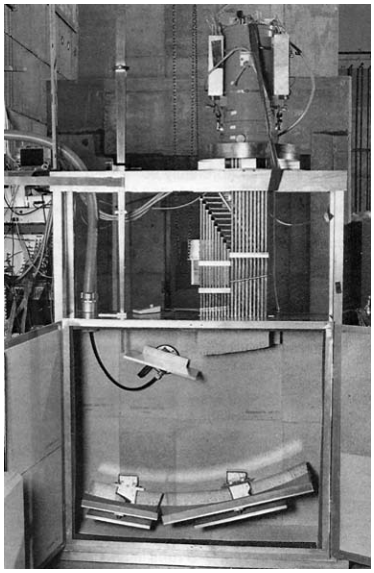
Edge measurements were also improved. Profile information of the electron temperature and density at the edge was significantly enhanced by a spectrometer with a newly available image intensifier in the Thomson scattering system. The ability to probe deeper into the edge plasma was increased by installation of a fast moveable probe by Denis Manos and Steve Kilpatrick. The survivability of its tips was much improved and allowed measurement deeper into the plasma. A fast infrared camera was added to measure temperature and monitor the energy deposition on part of the first wall. New NB pyrometer interlocks were added for the additional heating beams. A fast-scanning camera on the plasma TV system looking at D_α emission caught edge-density fluctuations for Stewart Zweben, who also installed the first prototype of the escaping alpha-particle/triton detector using a scintillator inside the vacuum vessel. The battery of fusion product measurements was enhanced by Ed Cecil and Sid Medley, who placed a gamma detector in a small concrete blockhouse on the test cell floor.



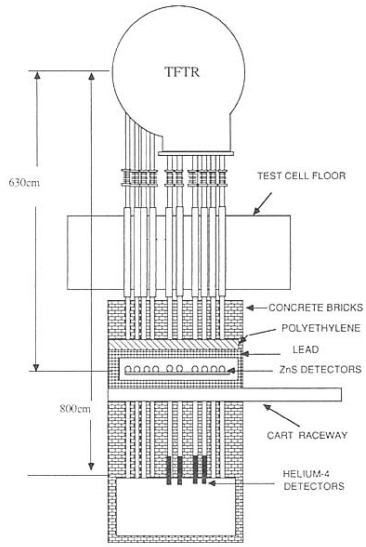
The shielding box surrounding the horizontal neutral charge exchange analyzer (86E0936).



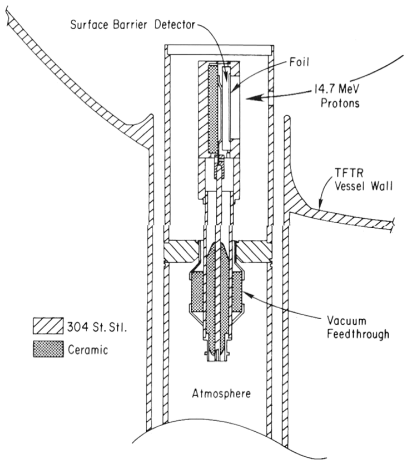
First effective measurement of a neutron emission profile in a tokamak (87X0151).



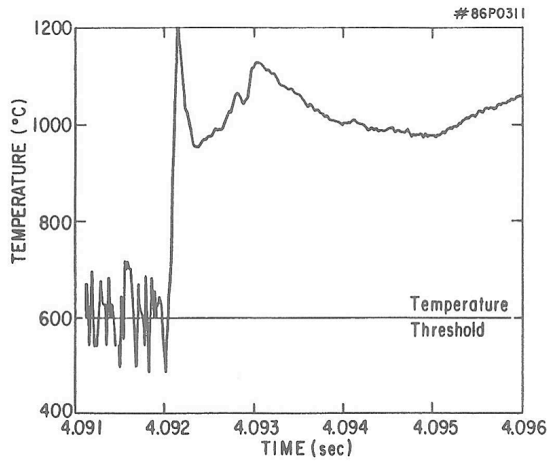
The spectrograph of the microwave grating polychromator (86X3301).



Drawing of the neutron collimator structure under the tokamak (McCauley & Strachan, RSI, **63**, 4536 (1992)).



First lost fusion-product (proton) detector on TFTR (Strachan, RSI, **57**, 1771 (1986)).



Infra-red camera measurement of the temperature rise of the bumper limiter surface at a disruption (86P0311).

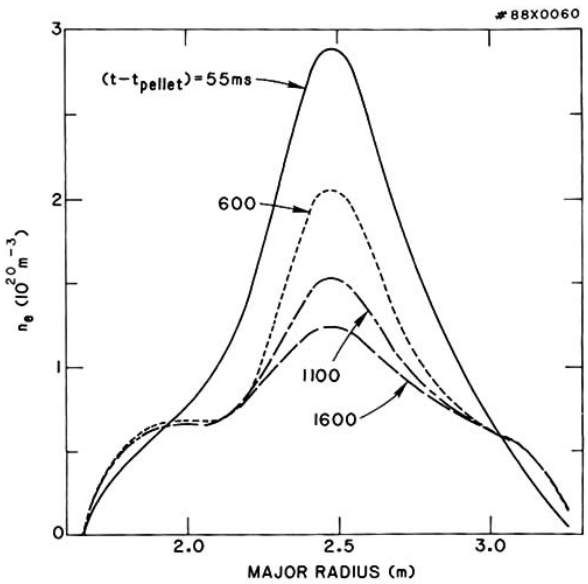
Fiscal Year 1987

The experimental program was now almost totally devoted to the study of supershots. Higher ion temperatures (up to about 30 keV) were obtained and it also became clear that the plasma performance was best with balanced co- and counter-directed injection of the heating beams. Since the current arrangement was with three beam lines in the co-direction (i.e. parallel to the direction of the plasma current) and one in the counter-direction, it was not possible to benefit from the full available input power. The arrangement of the sources in the neutral beam boxes meant that the radial profile of the heating power could be varied somewhat. With the extensive set of profile diagnostics, the transport properties of the plasma could be investigated. Pellet fuelling was also thoroughly investigated. A new constraint was added to the physics program in that pulse-lengths had to be limited, or program goals had to be modified, to limit the activation of the tokamak components by neutrons.

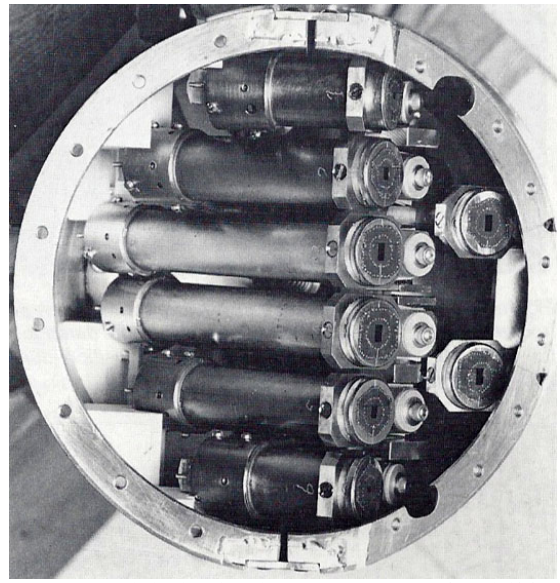
Operation of the tokamak had been very intense in the preceding year, so the early part of this year was used to repair and improve diagnostics and carry out routine maintenance. An operational period of a few months, spent in taking data and providing analyses for a highly successful operational period with long-pulse (two-second long) neutral beams was followed by a period for reorientation of a neutral beam box and installation of ICRF heating.

The CHERS diagnostic was operable with 10 cm spatial resolution using a heating beam and 5 cm resolution with the DNB near the edge. It produced both ion temperature and toroidal rotation results, closely in agreement with those from the x-ray crystal systems. Alan Ramsey added channels to the H_a array and visible Bremsstrahlung spectroscopic systems. The neutron activation system became fully operational. Jim Strachan used an NE213 proton recoil spectrometer in a large paraffin collimator on the test cell floor to make simultaneous measurements of 2.5 MeV neutrons from the D-D reaction, and 14 MeV neutrons from deuterons reacting with the fusion-product tritons (triton burn-up). Escaping tritons were measured for the first time by the prototype alpha-particle detector. A prototype radio-frequency

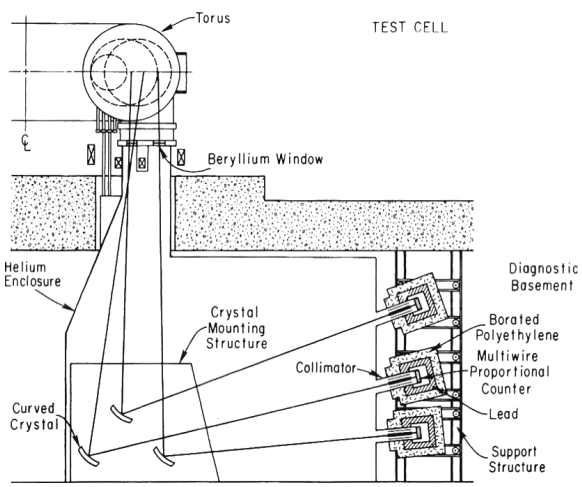
probe was mounted inside the vacuum vessel by Glenn Greene, with the expectation of being able to identify and follow fusion-product particles. Don McNeill installed a fast polychromator to study the density and temperature in the ablation cloud surrounding fuel pellets. However, the current density measurement making use of the Faraday rotation of the vertical interferometer beams proved very difficult despite help from C.H. Ma of ORNL.



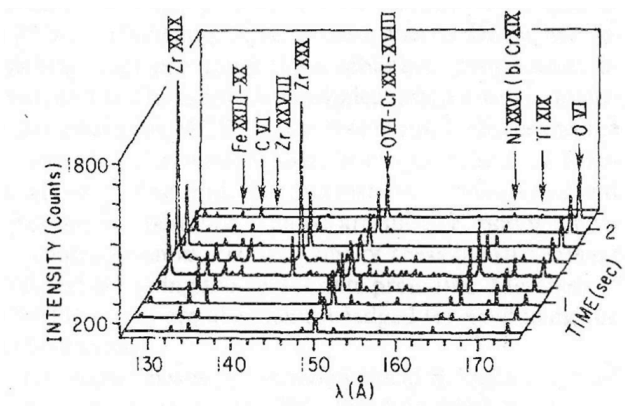
Evolution of the electron density profile after a single pellet was injected into an ohmic plasma (88X0060).



The tangential-viewing bolometer array (87E1622).



Schematic layout of the X-ray crystal spectrometer in the basement below TFTR (Bitter et al., RSI, **57**, 2145 (1986)).



Time-resolved emission in the UV range by SOXMOS showing a sudden emission of zirconium in the plasma due to its interaction with the getter (Schwob et al., RSI **58**, 1601 (1987)).

Fiscal Year 1988

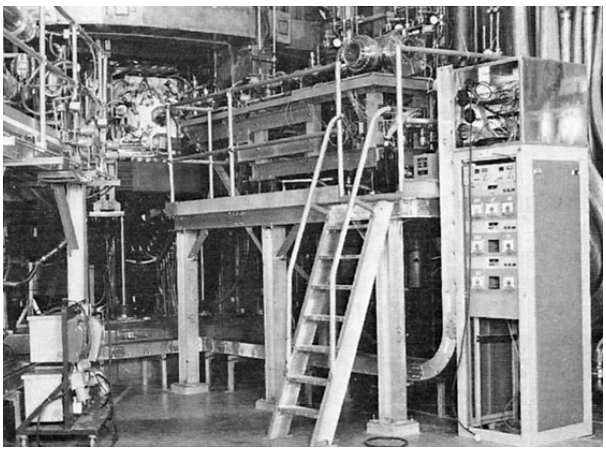
Plasma operation began in January 1988 with the co- and counter-orientation of the neutral beams now balanced, i.e. with two beam lines, each equipped with three beam sources, injecting tangentially in each direction. The first two ICRF antennae had also been installed. The resulting increase of power into the plasma led to erosion at the edges of some of the graphite tiles, showing up as bright light on the plasma TV. A cracked tile and slight damage to the limiter for the ICRF were identified through the inspection system.

The physics program was primarily devoted to the examination of the improvement in the confinement of the supershots with their relatively peaked densities and ion temperatures and flattish electron temperature profiles. Ion temperatures over 30 keV were observed. A peak neutron yield of 3.7×10^{16} was obtained. The capabilities of the diagnostics for time- and space-resolved measurements were heavily exploited in perturbative experiments for the elucidation of transport properties. The best supershots were obtained by injection of the beams into very low-density plasmas, so extensive studies were made of wall conditioning. Driving plasma current non-inductively by using the neutral beams was also studied because of its importance for future devices. The ICRF antennae, giving up to 3 MW of power, were brought on line with limited time for conditioning of the antennae.

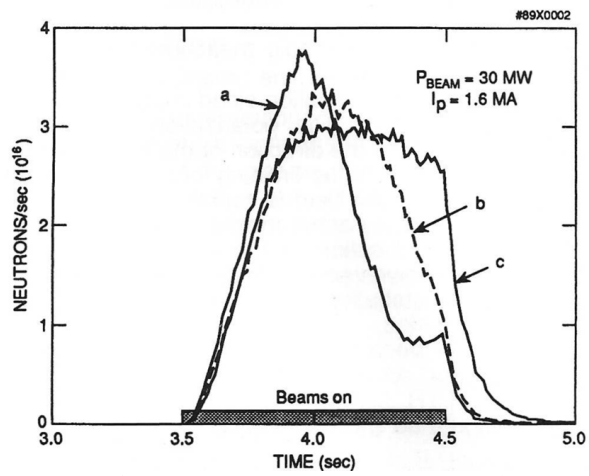
The extensive maintenance period at the start of the fiscal year and a change in the scheduling of the operational periods to two weeks on, one week off, led to a lot of improvement in the diagnostic operation. Many diagnostics were realigned and many improvements in the electronics were possible. A lot of time was assigned to calibration. A neutron generator, operating either as a D-D source or a D-T source, was moved inside the vacuum vessel to calibrate neutron diagnostics and check their relative sensitivities at the different energies. A major effort to improve the overall diagnostic operational reliability, necessary for the D-T operation, was begun. More detailed consideration of shielding for the diagnostics, still with the expectation that the concrete igloo surrounding the tokamak would be installed, was initiated. An electronic synchronization system was added to enable exact triggering of a number of diagnostics for studies of disruptions and other MHD phenomena.

Hiro Takahashi added an initial set of coils for studying very slow “locked-mode” magnetic phenomena. Norton Bretz devised a microwave scattering diagnostic using the extraordinary mode at a frequency of 60 GHz specifically for studying drift mode instabilities. The H_α array was realigned and now was accompanied by a similar array dedicated to looking at neutral carbon lines, carbon being the strongly dominant impurity in TFTR. Observation of deposition of a thin semi-transparent film on the quartz shutters of the Thomson scattering system prompted the installation of a calibration light source. Additional electrostatic analyzers were placed in the basement to add spatial definition to the neutral particle measurements. An enhanced lost fusion-product array revealed energetic particle loss due to strong MHD activity in the plasma. The radiated power measurements were improved with new arrays of tangential-viewing bolometers. Probing of the plasma edge was enhanced by adding sample exposure heads; the elements deposited on the probe tips were analyzed by Bill Wampler at Sandia National Laboratories. One of the new radio-frequency probes showed a broadband component on which were

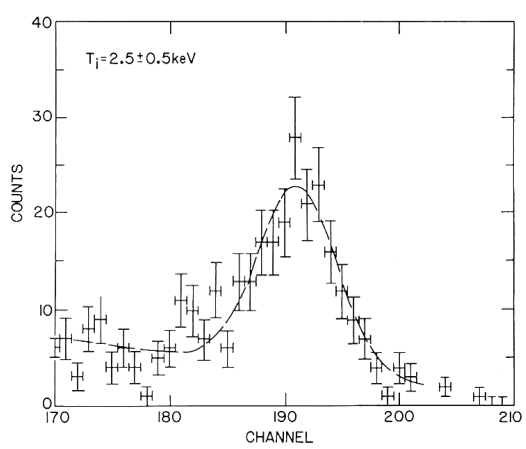
superposed resonant peaks fitting with emission from the low-field-side scrape-off region. Russell Hulse's MIST code was used to analyze the transport of impurity elements injected by the laser-blow-off impurity injector. Earl Marmar and Jim Terry from MIT installed an injector for lithium pellets in preparation for a measurement of the current density profile. The full capability of the 10 channel neutron collimator was achieved. A group of physicists spent a weekend loading its shield container with lead and borated polyethylene blocks, with the crevices being filled with polyethylene beads; some of the latter escaped briefly causing a skating hazard in the basement. The burn-up of tritium, i.e. the ratio of the number of tritons reacting to the number produced, was carefully measured by Jim Strachan and colleagues using the NE213 neutron spectrometer, because of the importance of understanding the confinement of the fusion products.



The lithium pellet injector during pre-operational testing (88E1184).



Neutrons from three TFTR D supershots: a) highest neutron source strength; b) highest neutron yield in a pulse; c) highest Q_{DD} (89X0002).



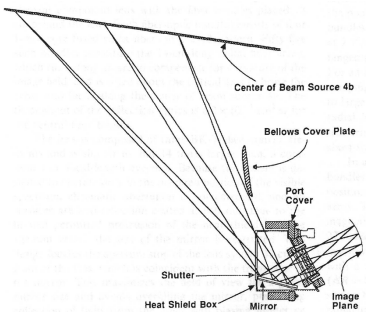
Neutron spectrum around 2.5 MeV using a He^3 ionization chamber (Strachan et al., RSI, **59**, 1732 (1988)).

"Not ready for D-T": Bob Hunter

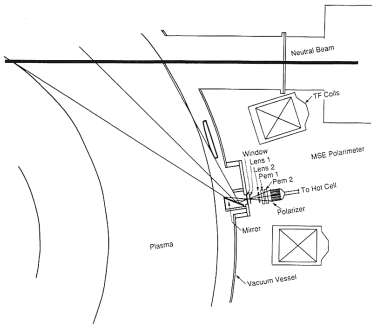
In November 1988, Bob Hunter, head of the DOE Office of Science, unilaterally decided that the results obtained to date on TFTR did not justify going forward with the D-T program. He withdrew a large fraction of the funding for the future program, managed by Roy Little, dedicated to preparation for D-T. This budget cut led to another reduction in PPPL staff, but did not affect diagnostics very much. But Hunter ordered that the United States should undertake a strong diagnostic development program to improve the physics understanding, particularly of thermal energy confinement, and authorized funding of better diagnostics in a national competition. Clearly alpha-particle diagnostics could not be considered.

Larry Johnson led an internal Diagnostics Initiatives Program to prepare proposals to be put forward for this DOE Initiative. Two of their three suggestions were approved with satisfactory funding. The first was the evolution of the single-channel MSE (motional Stark effect) diagnostic on PDX to a full-profile system for TFTR. Fred Levinton of Jaycor led this effort. The second was a new spectroscopic edge turbulence diagnostic, beam-emission spectroscopy (BES), to be built in collaboration with the University of Wisconsin in a group led by Ray Fonck. The unsuccessful third system, proposed by Ernesto Mazzucato and Raffi Nazikian in an all-PPPL scope, was a microwave reflectometry technique for measuring low-level density turbulence. DOE probably did not support this last because of a similar reflectometry proposal from UCLA for measuring edge-density profiles in DIII-D. However, the promise of this measurement was so strong that funding was found within the TFTR diagnostic budget, with ultimately with some help from savings in other areas.

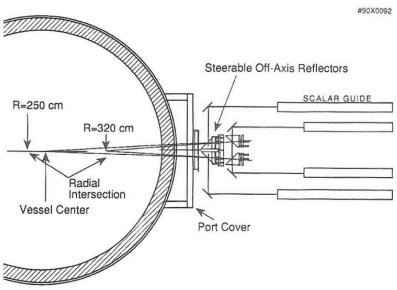
All three of these pioneering diagnostics proved their value when we ultimately headed to D-T operation.



Schematic of the sightlines onto a neutral beam for the beam emission spectrometer (BES) (Paul & Fonck, RSI, **61**, 3496 (1990)).



Schematic of the sightlines for the polarization measurement system of the motional Stark effect (MSE) system (Levinton, RSI, **63**, 5157 (1992).



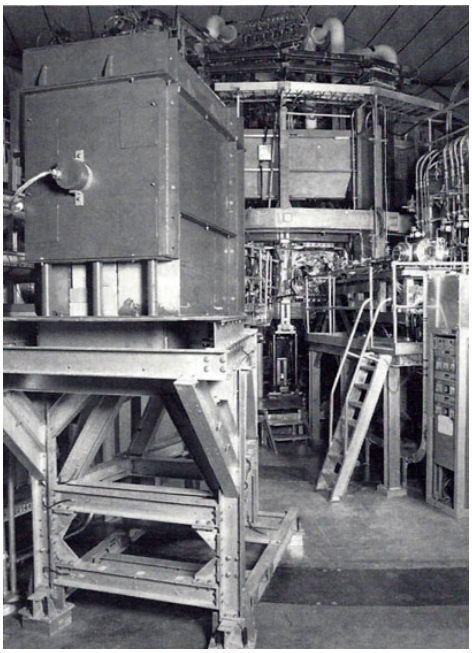
Optical arrangement close to the tokamak of the reflectometer system (90X0092).

Fiscal Year 1989

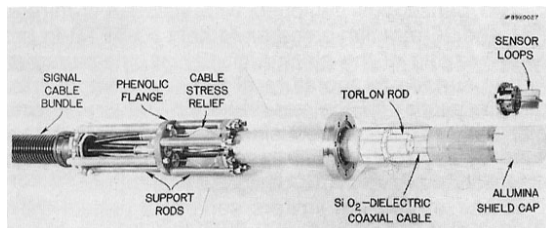
The direction of the TFTR program took a major turn because of Dr. Hunter's thinking. The emphasis shifted to extensive studies of plasma transport. Not only the good confinement supershots with their reactor-equivalent plasma parameters in their core, but high density pellet-fuelled plasmas, ICRF-heated plasmas, H-mode (high-confinement, defined mostly in tokamaks with divertors) plasmas, and even L-mode (low-confinement, universally obtainable in all tokamaks) underwent rigorous experimentation. Amongst this work were some detailed studies of the confinement of the fusion-product particles, clearly of importance for ITER and other future devices. The impurity pellet injector, mostly injecting lithium pellets, was a useful tool in these physics studies.

The clear emphasis on plasma transport, and the role of instabilities in it, led to a concentration on improving the fluctuation diagnostics. Upgrading the electronic data-processing of the microwave scattering system was put in hand. As indicated above, developments of a microwave reflectometer and a BES system were started, a prototype channel of the latter being tested on PBX-M. Even the electronics in the racks of the Mirnov coils were upgraded under Eric Fredrickson to improve reliability, noise levels and switching capability. A new low-loss waveguide in the grating polychromator radically improved the signal-to-noise ratio. Improved electronics were installed in the HAIFA system for observing fluctuations in the neutral hydrogen light emission.

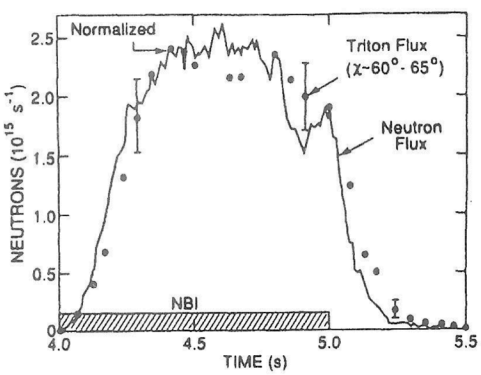
The tangential bolometer arrays were particularly useful following the injected fueling pellets. The new neutral particle analyzers came into their own in examining the high-energy tails of the ion energy distributions in ICRF-heated plasmas. The neutron diagnostics, especially the 10-channel neutron collimator, were in continuous demand. They had undergone an extremely detailed in-vessel calibration with an intense ^{252}Cf source being moved to many locations inside the tokamak. The fusion gamma diagnostic was moved to have a tangential view with its own major shield complex, and proved its value in ICRF-heated plasmas. The first current profile measurements by determining the polarization of Li^+ light as a lithium pellet penetrated the plasma were obtained. The laser blow-off (LBO) injector was used in transport studies of various impurities. The injector was also used to improve measurements by the x-ray crystal spectrometer, since the typical intrinsic iron impurity level had fallen too far to provide a sufficiently strong line emission signal. The LBO system, and a modification of it, such that the laser was focused on the inner bumper limiter to ablate material from its surface, were used for assessing the quality of the first wall during discharge cleaning and boronization of the vacuum vessel.



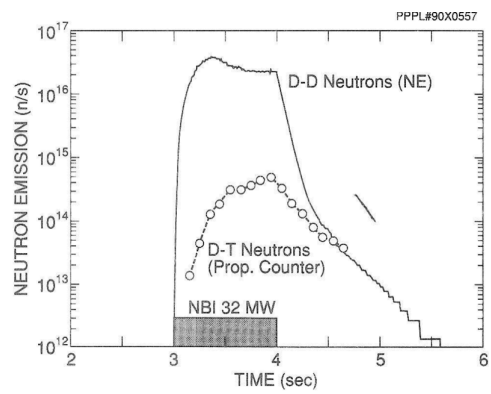
The re-arranged fusion gamma diagnostic in its shield box (89X3329).



The construction of one of the high frequency rf probes (89X0027).



Measured time dependence of the tritons escaping to one of the lost-α detectors compared to their production (neutron flux signal) (Zweben, Nucl. Fus., **29**, 825 (1989)).



Measured time dependence in a deuterium discharge of the D-D and D-T neutron emissions averaged over the supershots (90X0557).

Fiscal Year 1990

Excellent experimental results this year certainly contributed to the strong recommendation by the Fusion Power Advisory Committee that TFTR should be reset on its path toward D-T experiments. The tokamak had operated very reliably with record neutral beam power (33 MW) and RF power (6 MW). After replacement of the inner bumper limiter graphite tiles in critical areas with carbon/carbon composite tiles and a very careful alignment of these tiles, a record D-D neutron rate of 5.0 x 10^{16} n/s was generated in a supershot. This number was equivalent to a Q_{DD}~1.9 x 10^{-3}, which modeling showed should extrapolate to a Q_{DT} ~ 0.34 for a 50/50 D-T mixture. Electron temperatures over 10 keV were

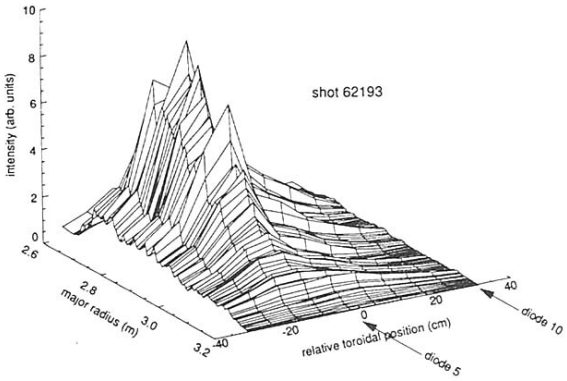
measured. During the year, accurate measurements of the neutron fluxes outside the Test Cell shield wall indicated that an igloo shield should not be necessary for a limited number of D-T shots and its installation was cancelled, reducing the cost and difficulty of preparing for D-T operation considerably. The year was also distinguished by the very large number of collaborators participating in the experiments, having been lured by the special quality of both the TFTR plasmas and its diagnostics.

Better control of impurities adsorbed on the limiter surface by employing plasma glows in diborane enabled a much shorter time period after a vacuum vessel opening before reaching full operational capability. It also became apparent that there were real benefits to preparing the wall by depositing small amounts of lithium on the limiter using the lithium pellet injector. The studies of transport in a wide variety of plasma types could be continued with a reliable diagnostic set enhanced with new fluctuation diagnostics. A new study of high-β_p plasmas by Jerry Navratil and Mike Mauel of Columbia University was started. Enhanced plasma position control was possible because of a change in the configuration and real-time processing of the magnetic diagnostics. The powerful transport codes SNAP and TRANSP added enormously to the effectiveness of the operations with their very rapid turn-around on understanding of the discharge behavior. While there had been a steady improvement in the amount of memory available in the CICADA system, a big step-up was a big help for the diagnostic output.

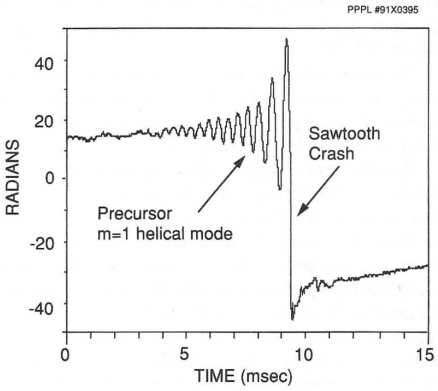
The new fluctuation diagnostics, BES and microwave reflectometry, became an important part of the arsenal of fluctuation diagnostics on the tokamak. Their results could be closely compared with those of the microwave scattering system. The x-mode reflectometer only operated in a single frequency prototypical mode. Higher speed response of the multichannel interferometer revealed new features in the ablation of the fuelling pellets. MHD studies were improved for both the x-ray imaging and the ECE by the use of improved tomographic analysis codes by Y. Nagayama of the University of Tokyo. Better understanding of the fluctuation spectra led to extending the frequency range for these and the Mirnov coils to over 1 MHz. The lithium pellet injector was also used in developing safety factor profiles, both by using polarimetry and by imaging the cigar-shaped cloud of Li^+ light onto position-sensitive diodes.

Spectral analysis of the neutron spectra by helium proportional counters had now been introduced into four of the multichannel collimator channels enabling differentiation of 14 MeV D-T neutrons from their 2.5 MeV D-D counterparts. A workshop was held with JET personnel and many others to discuss the success achieved in attaining satisfactory calibration of the neutron diagnostics, where TFTR's experience was clearly the most comprehensive. An escaping fast-ion probe was mounted on a moveable probe near the horizontal midplane to search for fusion-product particle diffusion induced by ripples in the toroidal field. The RF probes detected He-3 fusion products for the first time and the fusion gamma diagnostic, with its improved neutron shielding, proved effective in ICRF minority-heated discharges.

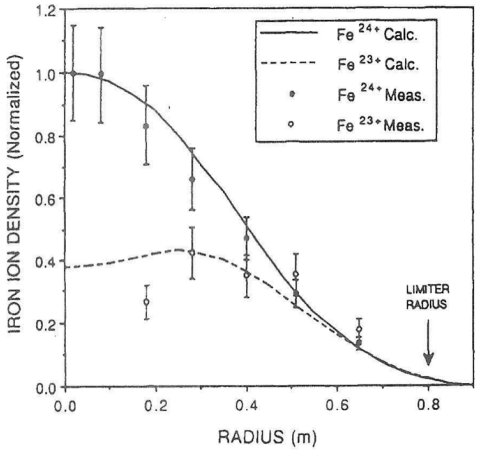
A review committee for D-T in TFTR supported important upgrades to the set of diagnostics for D-T operation. These included a gyrotron scattering system, a charge-exchange spectrometer for detecting fast helium ions (slowing-down alpha particles), new 14 MeV neutron detectors in the multichannel neutron collimator and improved escaping fusion product detectors. A full assessment of the significant impact on many of the diagnostics during D-T without the igloo shielding was begun.



The toroidal intensity distribution of the Li ablation emission as the Li-pellet penetrates the plasma (Terry et al., RSI, **63**, 5191 (1992)).



Phase time evolution of a wave reflected from the central region of a discharge in the presence of a sawtooth oscillation (91X0395).



Spectrally measured (dots) and calculated radial distributions of the densities of Fe^{24+} and Fe^{23+} ions 0.05 s after iron injection into the plasma (Stratton et al., Nucl. Fus., **31**, 171 (1991)).

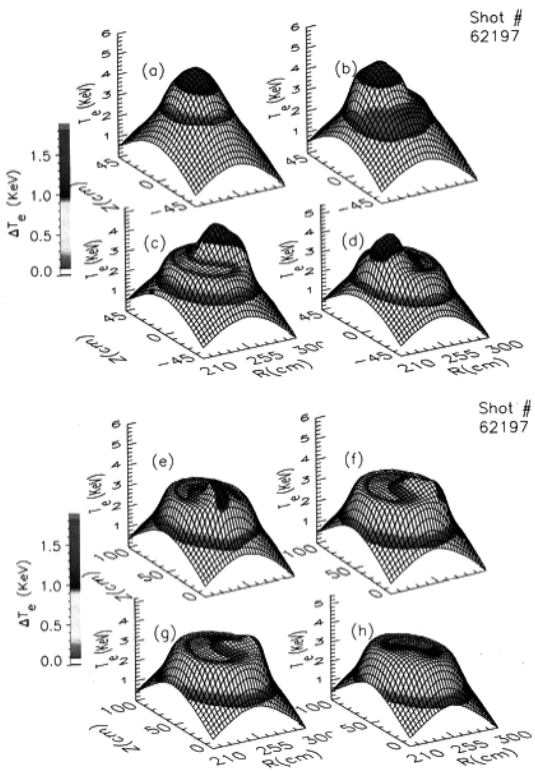
Fiscal Year 1991

The program in FY'91 was dominated by preparation for the D-T program, then expected to take place in 1993. Operations were limited to two months so that funding could be made available for necessary new hardware and for ensuring safe operation when tritium came on site. A visit by a "Tiger Team" sent by DOE, then under the leadership of Admiral James Watkins (USN-ret), to assess the laboratory's safety and environmental compliance, generated a massive amount of work, first in preparation for the team's visit in the spring and then in remediation of findings by the team. This was the first of many rigorous reviews conducted by outside teams and agencies in the run-up to D-T. Money and time were devoted to making the facility safer and to training staff in preparation for the somewhat different environment with tritium on site.

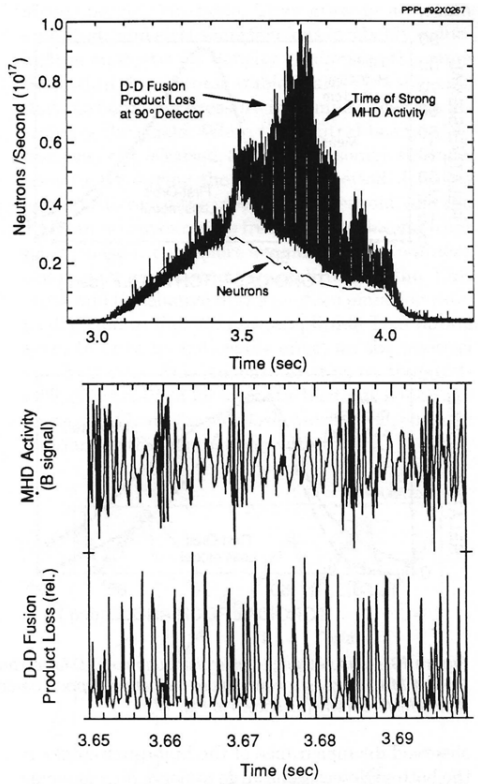
The abbreviated physics program nevertheless produced better plasma performance. Improved wall conditioning through more extensive and effective use of lithium pellets clearly made a big difference. Higher density plasmas, made available by the many-pulse deuterium pellet injector provided by ORNL, could be studied, and the high-β_p program was extended. Again, the emphasis for those, as well as for L-mode and H-mode plasmas, was on trying to determine the relationship between transport and fluctuations in the plasma. There was, of course, extreme interest in the observed effects on the fusion products. A new class of high-frequency instabilities, the toroidicity-induced Alfvén eigenmodes (TAEs), which had been predicted by theory, was identified experimentally. This prompted a refinement of the theoretical models in an effort to explain the observations.

To protect the ICRF antennas from direct exposure to the plasma, new limiter rings had been installed in the vacuum vessel near the location of the escaping alpha-particle detectors. To allow paths for the particles to reach them, the detectors had to be moved inward 2-to-3 cm, with the result that they needed mushroom-shaped graphite covers to protect them from the plasma. The microwave reflectometer was completed to strengthen the capability of measuring fluctuations. The reflectometer provided three fixed-frequency channels and one channel which could be stepped across the range of frequencies. Additional arrays of Mirnov coils at different toroidal locations inside the vacuum vessel made MHD mode identification more certain. The horizontal x-ray camera was moved inward toward the plasma to provide better measurement near the plasma edge, and a new analysis technique sharpened the quality of the interpretation of the images. Thomson scattering was improved such that its triggering was not affected by neutrons, and the background light for the edge system was cut by inserting doped ruby filters provided by the Kurchatov Laboratory in Russia.

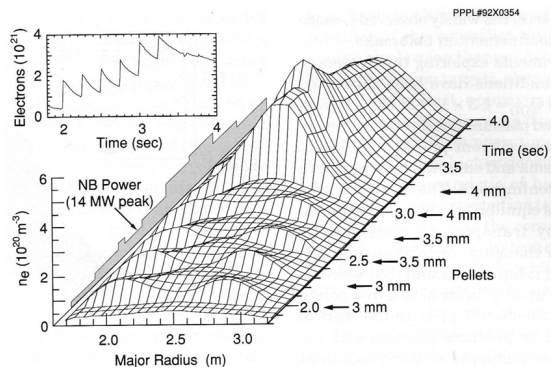
To improve measurement of the toroidal motion of the plasma, another set of optical fibers was added to the CHERS system to view a co-injecting beam. To provide some flexibility for the BES system, which had 100 fiber terminations at windows on the tokamak and initially had only 20 spectrometer/detector systems, an ingenious remotely controlled fiber-switching bank was installed. The Li-pellet injector, which was now used extensively for conditioning the wall with lithium, was modified to provide two pellets per pulse, and the pellet "cigar" monitoring system was improved to 10 operational channels for studying the q-profile.



Time steps of 80 μs for T_e profiles showing reconnection during a sawtooth crash (in color in Yamada et al., RSI, **63**, 4623 (1992)).



Example of MHD-induced loss of DD fusion products at the bottom detector (92X0267).



The evolution of the density profile arising from injection of six frozen deuterium pellets during neutral-beam injection (92X0354).

Diagnostic Preparation for D-T

The diagnostics were always designed with the ultimate expectation of operating in a very high neutron flux, though not integrated fluence because of the limited number of shots of relatively short duration. The concept of having a thick shielding igloo surrounding the tokamak, and the thick concrete floor between the tokamak and the basement provided the capability for having relatively modest shielding for

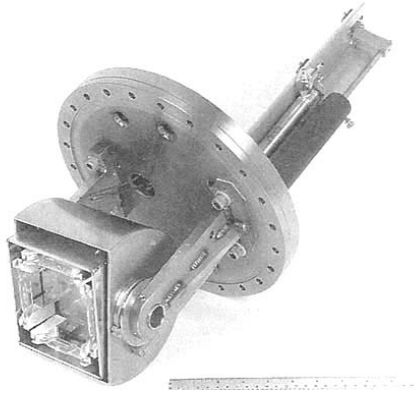
diagnostics in the test cell and basement. Standard electronic equipment could be used in the data-acquisition rooms without a need to purchase expensive radiation-hard electronic components.

Measurements of the radiation observed outside the test cell during the extensive deuterium operations showed that the measured dose levels were much less than had been predicted. Evidently the shielding provided by the large amount of equipment in the test cell and the one-foot thick panels of boronated concrete added to the walls had removed the need for the very expensive and obstructive igloo.

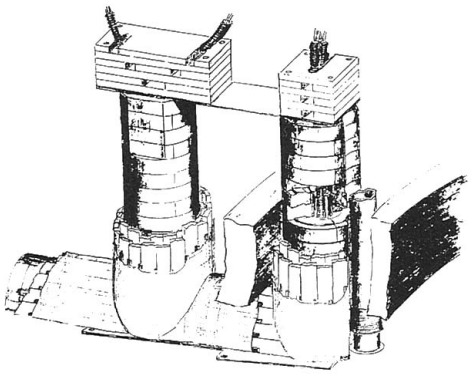
The assessments of neutron fluxes and fluences were very helpful in assessing the needs for shielding sensitive diagnostic components no longer shielded by the igloo. The quantity of shielding required for each diagnostic system was assessed in code calculations by Long-Poe Ku and his colleagues. In general, the shielding consisted of thick boronated polyethylene held in shells made of fire-retarded wood, with the detectors being closely surrounded by lead to remove the gammas generated in stopping the neutrons. Significant mechanical engineering was needed to assure seismic security.

Our philosophy was always that some components, such as optoisolators or TV cameras that could not be shielded and could be replaced by relatively cheap (not-radiation-hard) equivalents, would simply be allowed to become noisy or fail and then be replaced.

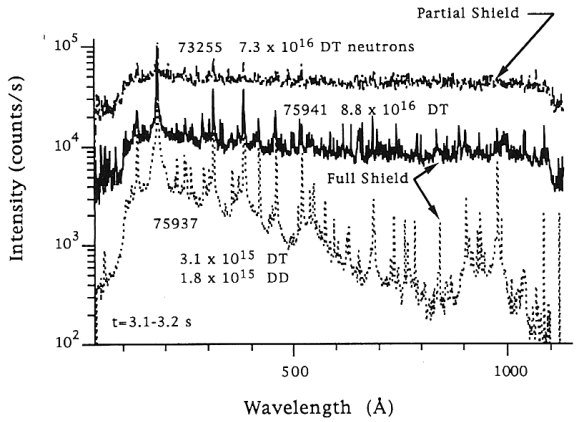
In one of the sequence of reviews which TFTR underwent, the key Tritium Readiness Review in November 1993, the reviewers delved so deeply into the issues for the tokamak, the tritium plant and the facility that the physics and diagnostics presentations were relegated to five minutes each at the start of the second day. (Note that printouts of all the planned 30-minute presentations were included in binders held by each reviewer.) Kevin McGuire's talk on the planned physics program did not get one question. But a voice in the audience asked Young why, if the purpose of the campaign was to study the physics of D-T plasmas, the FY1994 budget for diagnostics had been cut. Though not stated by any of the PPPL managers who rushed to answer, the real reason was that it was early in the fiscal year and most of the necessary diagnostic construction had been completed in FY1993 with judicious overruns in the budget.



Photograph of one of the remotely controllable lamps for lighting the inside of the vacuum vessel for D-T operation (Medley & Johnson, **63**, 4738 (1992)).



Sketch of the shielding structure surrounding the fiberoptics of the lost-α diagnostic immediately under the tokamak (Darrow et al, RSI, **66**, 476 (1995)).



The impact of neutrons on the UV spectra in the SPRED survey spectrometer about 5 m from the tokamak. The full shield added 3" of lead and 3" of borated polyethylene around the whole instrument. The partial shield was 4" of lead and 8" of polyethylene around the detector only (Hill et al., RSI, **66**, 913 (1995)).

Fiscal Year 1992

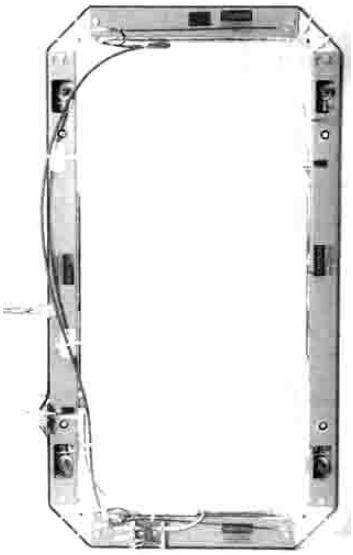
Despite limited operational time, again because of the emphasis on preparation for the safe performance of the D-T program, this was a very active year. An environmental assessment critical to the performance of a D-T program was approved and a Final Safety Analysis Report was formally reviewed. The Laboratory management held meetings with officials from the surrounding neighborhood to gain their support for the experiments and continued with this outreach for the remainder of TFTR's life. The very popular "Science on Saturday" series was started as part of this outreach.

The main hardware improvement to the tokamak systems was the addition of more ICRF antennae to double the available power into the plasma. Changes were also made to the neutral beams so that they could inject tritium. ORNL delivered a new deuterium pellet injector capable of delivering four pellets in a plasma pulse. Exploration of the boundaries on high performance of supershots and of high-β_p discharges, rehearsals of scenarios to be studied in D-T and in studies of the heating by ICRF consumed most of the operations. Instabilities and their effects on plasma and fast-ion loss were a continued focus. Studies of disruptions, so critical to be avoided for any future device, were enhanced by having the newly-installed MSE diagnostic able to measure the q-profile prior to the terminating crash. The hard x-ray detectors, deployed at TFTR since its early operation, were important in evaluating the runaway electrons generated in the disruption. Very careful measurements of the radiation background in the test cell and surrounding areas during operation were made to assist in the definitive planning of D-T operations.

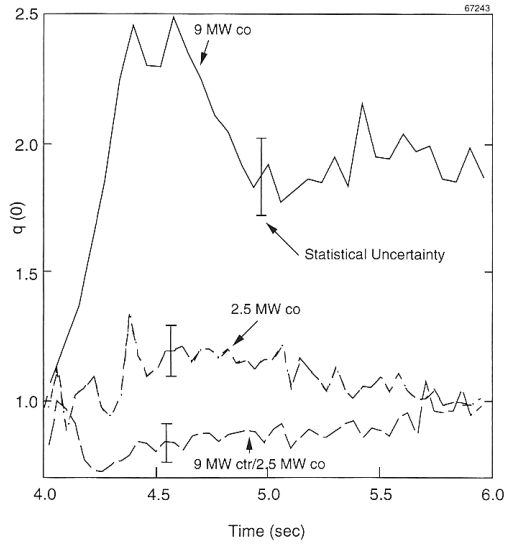
This year saw a slight change in course in the diagnostic program, with more funding going toward development of alpha-particle diagnostics. The lithium pellet injector was moved so the pellets would cross the viewing lines of the pellet charge-exchange system. This scheme was conceived by Ray Fisher

of General Atomics to detect energetic neutral helium atoms generated by double charge-exchange between fusion alpha particles and the dense neutral cloud surrounding an ablating lithium pellet. The α-CHERS spectrometer for measuring slowing-down alpha particles was tested on ICRF-accelerated $^{3}He^{++}$ ions in deuterium discharges. The design of a microwave collective Thomson scattering system for the full alpha particle distribution function made a lot of progress in collaboration with John Machuzak of MIT. An upgrade was made to the HAIFA optical system to enable it to selectively separate the H_α, D_α and T_α light contributions to permit analyses of the fuel mix. The escaping alpha particle diagnostics were reinstalled with better heat-tolerating graphite-mushroom heads and better scintillators incorporating reflective backing. Tests of the compensation for neutron/gamma effects in fiber optics were begun.

Better instrumentation was also provided for other plasma parameters. The MSE diagnostic for measuring the current density profile came on-line. Improvements were made to the magnetics diagnostics with new analysis hardware and software for the Mirnov loops, and a new array of coils for measuring stationary magnetic perturbations was added at one of the equatorial ports. Addition of anther channel to the reflectometer allowed the radial correlation lengths of density fluctuations to be measured. The BES spectrometers now operated with 28 individual detector systems. Because of concerns about the ability of the soft x-ray cameras to provide data through the upcoming D-T discharges, it was decided that a second grating polychromator should be installed to evaluate toroidal mode structure of the fluctuations. The x-ray crystal spectrometer was used to study krypton emission lines since krypton radiation had been proposed to protect ITER's divertor. A new 16-channel array of fast spectrometers for studying ablation of both fueling and lithium pellets took its first data at the end of the year. A re-entrant end into the vacuum vessel was a modification of the neutron activation system. A remotely controllable illumination system was installed to allow inspection inside an activated vacuum vessel by the plasma TV.



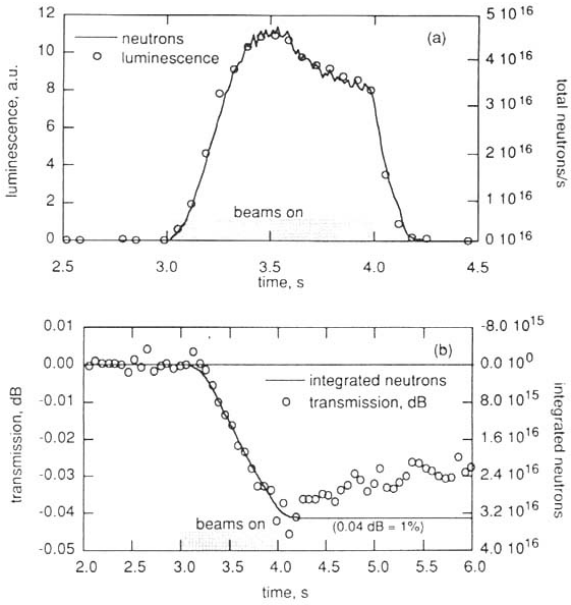
A picture frame-shaped coil (dark strand on the outside of the frame) for measuring slowing-down MHD modes (92E0590).



The MSE system showed that large values of q(0) could be generated by strong co-injection of neutral beam power (93X0309).

Radiation Impact on Fiberoptics

Optical fibers were distributed throughout the test cell and basement and hence would experience unknown effects in the high neutron fluxes. Neutrons, and the associated gammas from the neutrons being scattered, cause increased absorption while simultaneously causing broad-spectral luminescence in optical fibers. It was known that fused quartz fibers were the least responsive to radiation of different fiber types and hence all the fibers used in the test cell and basement were of this type. But at the TFTR radiation levels, significant effects were still expected. Alan Ramsey and his group set up an innovative experiment during the D-D operation to quantify the impacts to be expected during D-T. Dummy fibers, run parallel to the instrumentation fibers, ad an associated light, could be used to extract the two contributions during a pulse. All TFTR instrumentation was modified to benefit. This research, including analysis of long-term recovery of the absorption, led into a major international study undertaken for ITER. During D-T operation a further study of the use of heated fibers to reduce the absorption impact was carried out with Phil Morgan for JET.



The impact of neutrons on fused quartz fibers demonstrated during a D-D plasma on TFTR. Concurrent a) luminescence, and b) absorption (Ramsey et al., RSI, **66**, 871 (1995)).

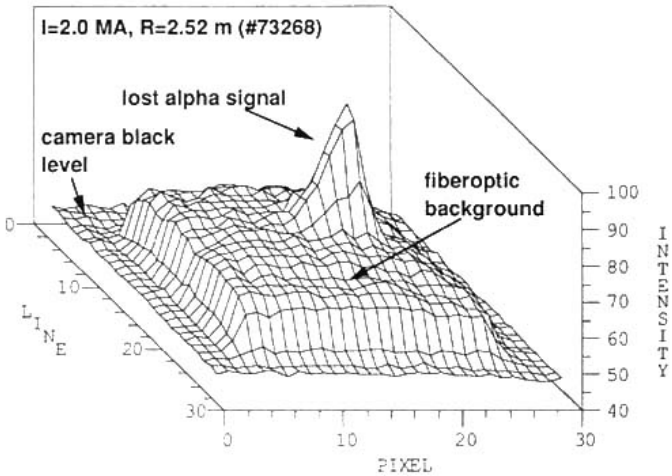


Image of the scintillator light from a lost-α probe. The background in the fiberoptics is caused by the neutrons (Darrow et al., RSI, **66**, 476 (1995)).

Fiscal Year 1993

Fiscal Year 1993 was critical for the demonstration of the possibility of carrying out D-T experiments in TFTR. The first half of the year was largely spent in hardware improvements for many TFTR systems. Concurrently, there were reviews, environmental assessments, and documentation, all in preparation for higher neutron levels and tritium being used in the tokamak. The key Operational Readiness Review

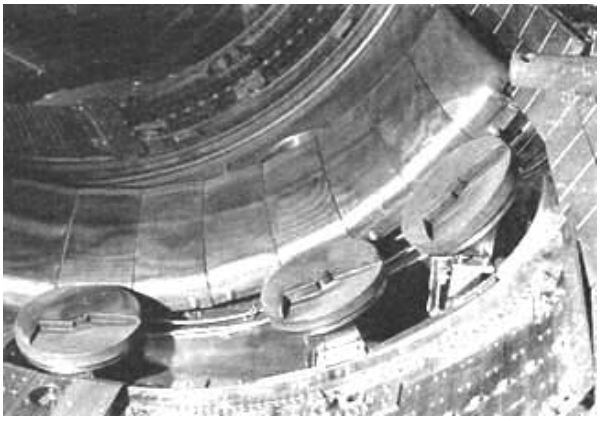
was passed in June. The review panel was generally satisfied with the range, capabilities and readiness of the diagnostic systems for D-T operation. However, there was a compulsory stand-down of the Laboratory in September because of three safety violations. Training in many areas would be key to ensuring a safe facility for everyone involved in the Laboratory and the surrounding area.

During the outage at the start of the year, many of the penetrations through the thick concrete test cell floor, initially provided for flexibility in mounting equipment, were filled and sealed to reduce the neutron streaming and to prevent possible tritium migration. This actually improved the environment for diagnostics in the basement. Many tokamak systems were upgraded. Testing and conditioning of all contributing systems was carried out. After all this work had been completed and the final configuration of the tokamak and its surroundings were set, a final neutron calibration with a ^{252}Cf source and a D-T generator in the vacuum vessel was carried out in February 1993.

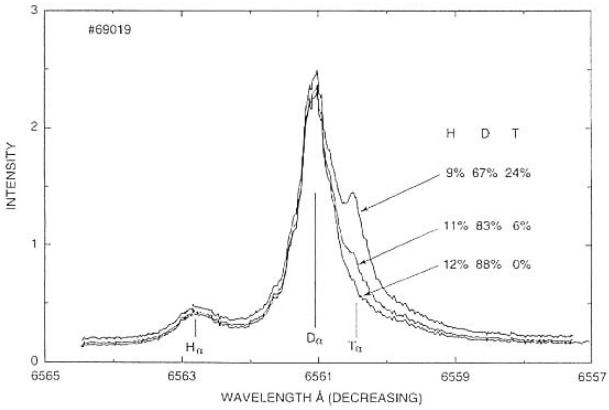
The experimental program was almost totally devoted to preparing plasma scenarios in deuterium which would realize a power level of 5 MW in D-T. Scenarios which were unlikely to suffer disruptions and which minimized adverse effects of MHD were developed. Conditioning of the wall by lithium pellets became an accepted necessity. Very extensive analyses of long-wave turbulence using the BES and correlation microwave reflectometer were carried out, and the escaping fast ions in D-D plasmas were used to project the anticipated losses of alpha-particles.

For diagnostics a very large fraction of the installation work was devoted to additional shielding, and mounting of seismically qualified stands in the test cell. Fiber-optic bundles were modified to ameliorate effects of the neutrons and gammas in the test cell. A spare fiber from the HAIFA diagnostic was instrumented with a Fabry-Perot interferometer by Charles Skinner for measuring tritium recycling by high-resolution spectroscopy of the H emission. One of the BES fibers was incorporated into a high-frequency CHERS system to be able to measure fluctuations in the ion temperature and parallel velocity. Tests of running fiber-optics hot (at ~ 400°C) to reduce the absorption of light caused by the neutrons proved promising for later installations on JET and TFTR. The Mirnov coil system was modified with additional coils and some relocations to give better determination of toroidal wave numbers. Their frequency response was also improved to 2 MHz to better detect high-frequency AE modes. The pellet charge-exchange system was completed. The low-power collective scattering system for alpha particle studies was installed. A novel diagnostic using luminescence in fiber optics from LANL was added to the collection of detectors in the multichannel neutron collimator. Many of the other detectors had been modified or changed out. Also into this collimator was added a new spectrometer, COTETRA, developed by M. Osakabe of NIFS in Japan. A pair of depleted silicon diode detectors was deployed, one in the horizontal collimator and the other outside, and demonstrated their ability to discriminate 14 MeV neutrons clearly with a very wide dynamic range in count rate.

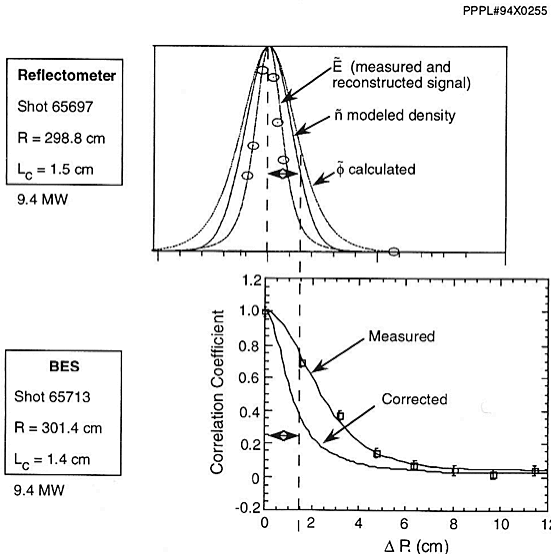
In preparation for D-T, Dick Palladino prepared an anthology, in engineering drawings and photographs, of all diagnostic ports on the tokamak to give guidance, if ever needed, to resolve any issues in the high-activation locations. They were not needed.



The three lost-alpha particle detectors in their final configuration at the bottom of the vacuum vessel (Darrow et al., RSI, **66**, 476 (1995))).



Fabry-Perot spectrum of light from hydrogen isotopes, showing T component (Skinner et al., RSI, **66**, 646 (1995)).



Comparison of the radial decay lengths of the turbulence in a supershot plasma by correlation reflectometry and beam emission spectroscopy (BES) (94X0255).

Alpha-Particle Diagnostics

Jim Strachan, Bill Heidbrink and their colleagues had already begun to study fast ions produced in D-D reactions in PLT and PDX and so laid a strong foundation for the powerful set of measurements of the alpha particles on TFTR.

The alpha particle source profiles were measured using the high spatial-resolution neutron collimators. Scintillator probes, developed by Stewart Zweben and Doug Darrow, were installed to measure alpha

particles escaping to the wall. These enjoyed considerable evolution because they had to be close to the plasma edge. The final versions had the encased detector scintillator and optics capped by a thick, specially machined graphite "mushroom." Heavy shielding of the optical fibers between the tokamak and the floor was necessary to reduce the neutron-caused background light relative to the fluorescent signal. Another probe for detecting the escaping alphas was a foil-deposition detector developed by Hans Hermann as his thesis project, which had the advantage of being more tolerant of radiation but needed to be removed for analysis and clearly could not provide time-resolved data.

The measurement of the confined alpha particles provided some good challenges. Thermal helium atoms in the core of the plasma were of interest because the build-up of helium ash from the fusion reactions could stifle the burn in a reactor. Ed Synakowski used the standard CHERS diagnostic to measure the spatial profile and infer the diffusion of the helium atoms. It also proved possible to measure the slowing-down alphas using the long wavelength side of the neutral helium 578.6 nm spectral line emitted by alphas exchanging charge with the neutral heating beam atoms. Ray Fonck (U. Wisconsin) and Brent Stratton led the effort of implementing this new α-CHERS system.

As previously mentioned, a system whereby alpha particles exchanged charge with lithium atoms in an injected pellet to be analyzed in a neutral particle analyzer came to TFTR from Ray Fisher (GA), who called the system PCX for pellet charge-exchange. The pellet injector, capable of firing two pellets in a TFTR pulse, was developed earlier at MIT. The Li pellet moved at about 400 m/s, which allowed for good spatial resolution. The analyzer which had evolved from the TFTR charge-exchange analyzers was built at the Ioffe Institute by Mikhail Petrov. The very low cross-section for this double charge-exchange reaction was compensated by the very high density of the atoms in the pellet's ablation cloud.

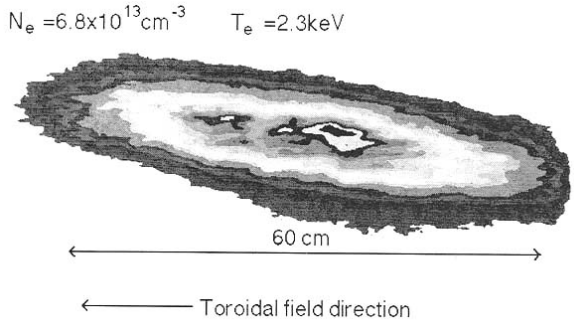
A less successful attempt at measurement of the alpha particles on TFTR was collective scattering of microwave radiation from the alphas since this could only be a small component of the scattered signal from the plasma. Unfortunately, in our attempt, made in a collaboration with John Machuzak of MIT, the available power source of 200W was too weak to provide a detectable alpha-particle signal. With a much stronger power source at JET, Henrik Bindslev managed to detect an alpha signal by averaging over many shots.

Alpha-particles when slowing down transfer energy to the deuteron and triton ion densities, leading to high-energy tails in their velocity distributions that affect the energy distribution of the neutrons produced by subsequent D-T reactions. The neutron spectra for energies above 14 MeV thus contain information on the confined alpha particles. This weak signal should be about a factor of 10^5 smaller than the primary 14 MeV peak. Ray Fisher installed an array of threshold bubble chambers close to the vacuum vessel to make spectral measurement of the neutrons. Unfortunately, the chambers that he used did not meet their specification and their low energy cut-off was not as sharp as needed to provide a satisfactory measurement.

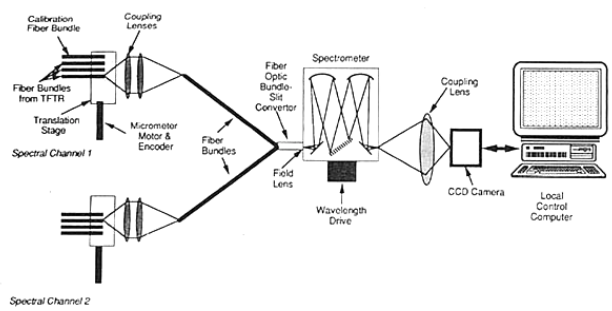
Studies on PDX had shown a relationship between some fast ion losses and bursts of radio-frequency emission. Glenn Greene had previously installed seven coils for the frequency range
5 – 500 MHz to measure ion cyclotron emission (ICE) at the top and bottom of the vacuum vessel and observed that they all provided some sharp spectral resonance peaks on a background continuum, with

the resonances corresponding to ion species passing through the scrape-off layer at large major-radius. In D-T operation, Steve Cauffman and Dick Majeski found that the early signals of the fusion-product alpha particles appeared to die away after about 100 ms and be replaced by signals consistent with the beam ions, a result still not fully understood.

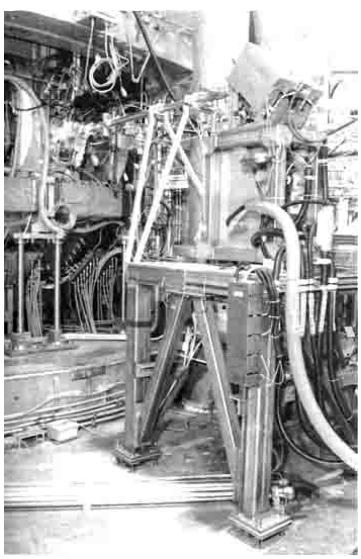
Some of these alpha particle diagnostics should only be considered as prototypes, because there was not enough time to resolve some measurement problems before TFTR was terminated. The pellet charge-exchange system, for example, could not operate usefully during neutral beam heating because the pellet ablated too rapidly. Neutrons and gammas caused a background light level in the fiber optics of the scintillator detectors that were used to observe escaping alpha particles. More seriously, background light in the fibers of the α-CHERS diagnostic was too large during the beam heating, making measurement of the alphas only possible after the beam was turned off.



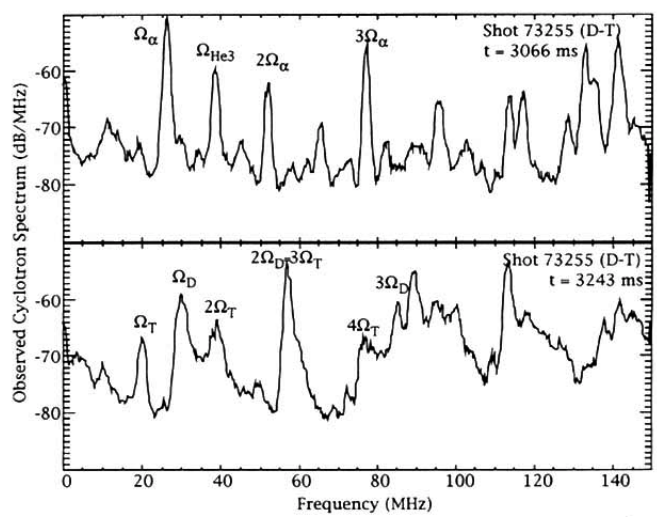
Light intensity contours of Li^+ of the ablating lithium cloud as the pellet of PCX penetrated the plasma (Fisher et al., RSI, **63**, 4499 (1992).



Schematic drawing of the α-CHERS spectrometer (Stratton et al., RSI, **63**, 5181 (1992).



The PCX detector to view pellets from the MIT Li-pellet injector (92E0713).



ICE spectra in a D-T pulse showing alpha -particle signatures early in the beam pulse, no longer visible later in the pulse (Cauffman &Majeski, RSI, **66**, 817 (1995)).

TFTR scientists watching computer monitors for the first D-T discharge (84A0232).

Milt Johnson (DOE Area Office), John Willis (DOE) and Rich Hawryluk celebrating. Behind them are Steve Eckstrand (DOE) and Jim Anderson (LANL).

Fiscal Year 1994

The fiscal year started off on a celebratory note as Russell Hulse, who did spectroscopic modeling for TFTR diagnostics, was awarded the Nobel Prize with Joseph Taylor for their discovery of the first binary pulsar while Russell was a graduate student.

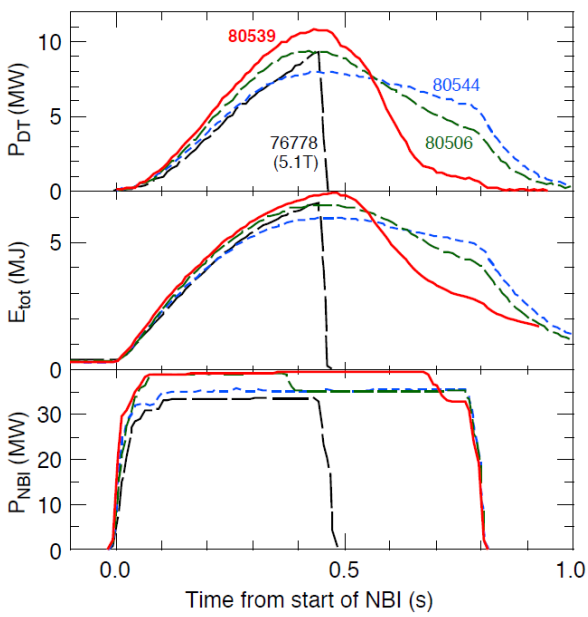
This event was followed almost immediately by the start of "trace-tritium" experiments in TFTR, where about two percent of the fuelling gas was tritium, roughly doubling the yield of neutrons from the plasma. Ten days were spent studying such plasmas, checking out plasma behavior and the quality of diagnostic and tokamak system operation.

Finally, on December 9, 1993, the first discharges with approximately equal fuel densities of tritium and deuterium were produced. The first shot at 5 p.m. produced 0.8 MW of power in the neutrons and by midnight 3.9 MW had been achieved in a later shot. On December 10, 6.2 MW was achieved and on May 27, 1994, 9.3 MW was reached. A posse of news reporters witnessed the December 9 shots.

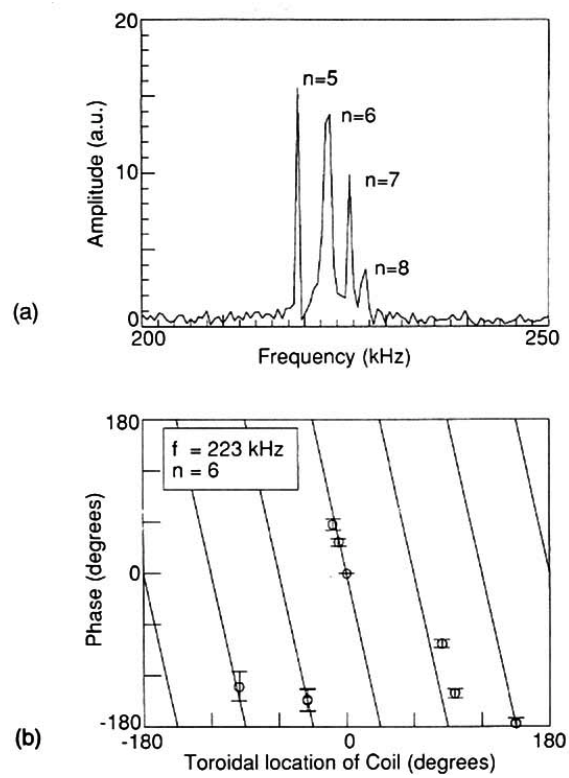
A very satisfying aspect of this period was the improvement of the operational performance of the whole TFTR system. Safe operation in D-T was very satisfactorily demonstrated and established. Good fusion performance was routinely obtained using neutral beams and the peak D-T fusion power was increased to 9.3 MW in May, although that shot ended in a massive disruption. The best performance was achieved by optimizing the lithium pellet wall conditioning. ICRF heating of D-T plasmas was demonstrated and the capability for more ICRF power was added. However, in September, during ICRF system conditioning, high-energy ions accelerated by the ICRF and trapped by ripples in the toroidal field drifted onto the bottom of the vacuum vessel and caused leaks in welds. Fortunately, it proved possible to repair the leaks without opening the vessel. Repairs were also needed inside the neutral beam sources and these were carried out safely despite the initial tritium contamination. The cooling water in the field coils was

replaced by a dielectric fluid, Fluorinert, in order to remove concerns about any reduced electrical resistance caused by small internal water leaks which had developed and been detected a few years before.

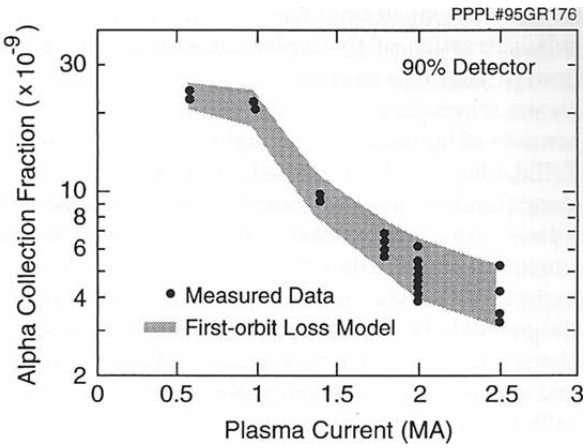
For diagnostics, the emphasis this year was on measurement and interpretation with very little installation. One result was the very much better operational reliability of the whole diagnostic system. Fusion-product studies dominated the action. These studies ranged from a simple scintillator behind a mask announcing fusion power from the D-T neutrons to detailed measurements of the confined alpha particles. Data was obtained on a) fusion yield and power production; b) alpha-particle source profile, c) escaping alpha particles; d) slowed-down confined alpha-particles by α-CHERS; e) alpha and triton energy spectra by pellet charge-exchange; f) MHD and TAE-mode activity; g) tritium transport and alpha-ash transport, and h) tritium influx from the limiter. The set of fluctuation diagnostics performed well through all the D-T shots. The x-ray cameras, blinded by noise during periods of high 14 MeV neutron emission, recovered quickly for operation during D only shots. All spectroscopic systems provided good data.



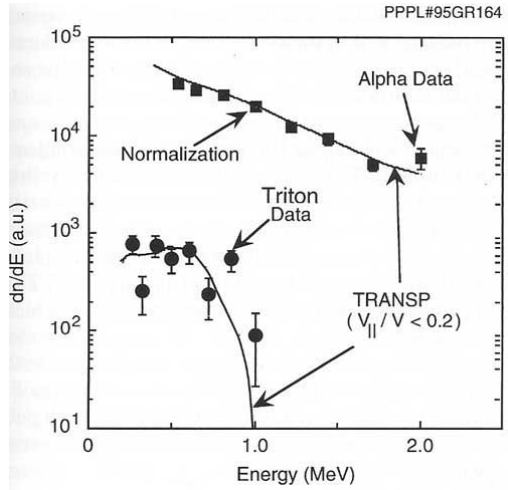
Some TFTR DT shots in 1994 on the way to the 10.7 MW power achievement.



Spectrum of a TAE mode driven by ICRF heating and fitted to a toroidal mode number of 6 (Fredrickson et al., RSI, **66**, 813 (1995)).



The α-particle loss fraction captured by the lost-α detector at the bottom of the vacuum vessel (95GR176).



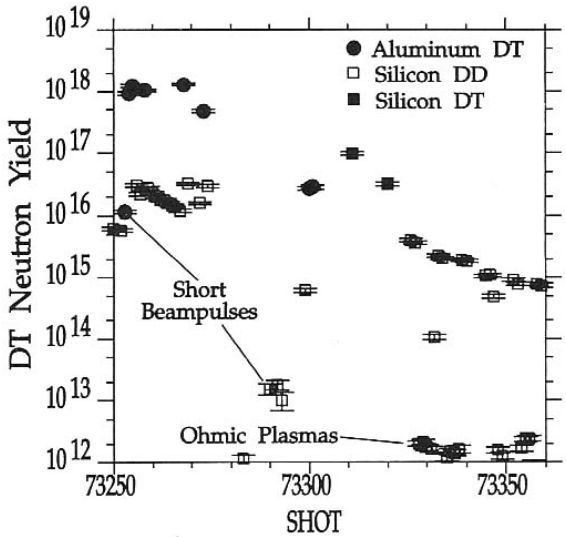
Confined alpha-particle energy spectrum in a DT discharge compared to that of confined product tritons in a D discharge (95GR164).

Fiscal Year 1995

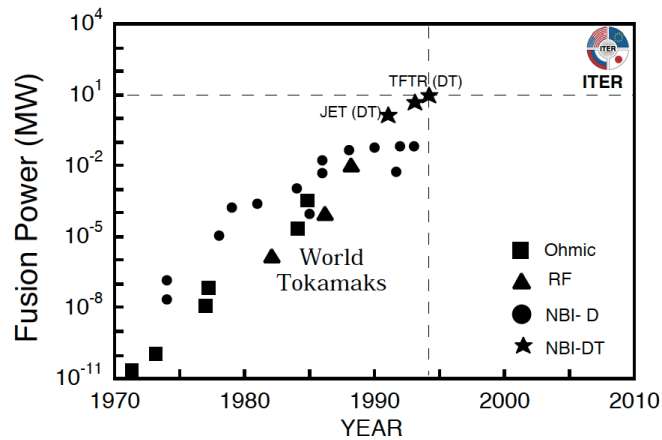
The successes in the operation in FY'94 were recognized by the TFTR program, long under threat of being shut down, being extended into FY'96. At the beginning of FY'95, in a campaign to maximize the fusion power production, the toroidal field strength was increased to 5.6 T (10 percent above the "nameplate" rating of TFTR), and the neutral beams, which operated more reliably in tritium, achieved a total injected power 40 MW. Both of these achievements reflected the dedication and ingenuity of the Engineering Division in supporting the experimental program of TFTR. In November, the output from D-T plasmas was raised to 10.7 MW in a supershot, which, in its core, very closely matched the fusion power density expected in ITER. The ion temperature peaked at ~ 45 keV and the pressure at the plasma center reached about 6 atmospheres. For the remainder of this fiscal year the research concentration was more on the operation of reversed shear plasma and high internal inductance plasma modes. Again, despite the outstanding science, the budget was cut, leading to layoffs of some important members of the diagnostics staff. David Johnson became responsible for the management of the Diagnostics Division.

During the year a new array of four sightlines was added to the multichannel neutron collimator to provide much better spatial resolution near the plasma center, of obvious benefit for supershot plasmas. Other changes were made to the detectors, including the first time that natural diamond detectors, provided by Anatoli Krasilnikov (Triniti), were used for neutron spectroscopy. Since it was no longer possible to use a neutron generator inside the vacuum vessel for calibrations, the new channels were calibrated using plasmas being "jogged" horizontally so channels could be cross-calibrated. The addition of new windows to an activated vacuum vessel was quite complicated.

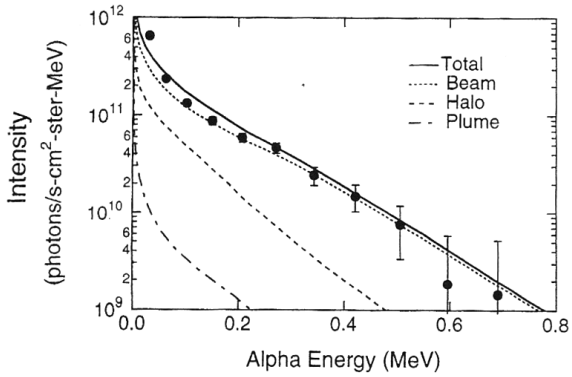
For the reversed shear plasmas the MSE diagnostic provided the critical data for analyzing their behavior. The microwave reflectometer revealed new information about fast magnetosonic waves.



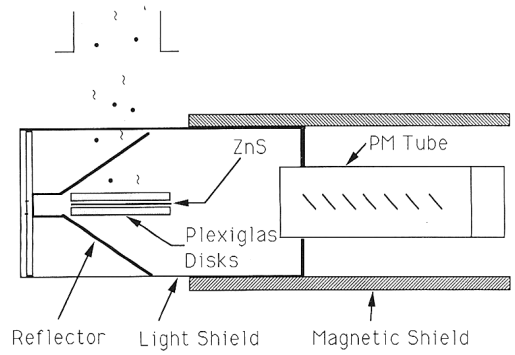
The very wide dynamic range of the neutron activation system in measuring the neutron yield in a pulse (Barnes et al. RSI, **66**, 888 (1995)).



The increase in fusion power since the ST tokamak demonstrated by neutron measurement for JET and TFTR (McGuire et al., APS 13195 (1994)).



The spectrum observed at r/a=0.3 in a supershot showing modeled components comprising the spectrum for α-CHERS (Stratton et al., RSI, **66**, 269 (1997)).



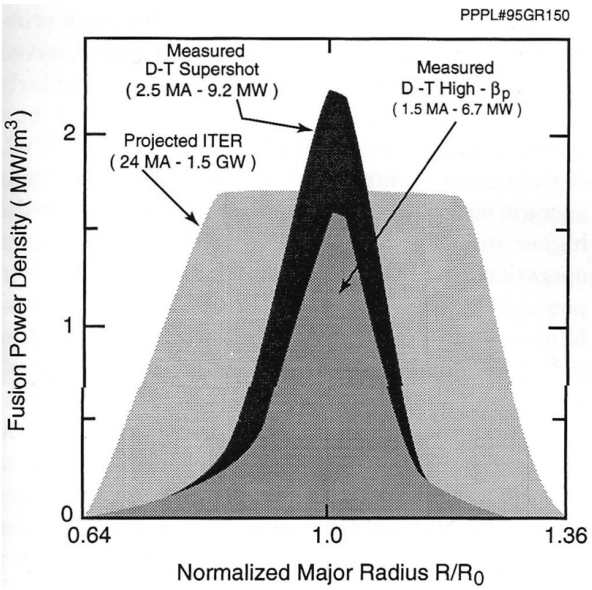
Design of the ZnS wafer neutron detector with low sensitivity to gammas. These detectors were developed for use in the multichannel neutron collimator (Roquemore et al., RSI, **66**, 916 (1995)).

Fiscal Year 1996

In a major shift in its emphasis, the DOE Fusion Program was restructured to focus on science rather than plasma performance. The impact of this was that TFTR was to be terminated in one year, independent of

the quality and relevance of its results. Meanwhile. TFTR pursued its pioneering science studies in reversed shear plasmas and high internal inductance plasmas. For the former, studies were largely devoted to developing understanding of the transport barrier that was evident in the Enhanced Reverse Shear (ERS) discharges that had been discovered in TFTR. The value of the high internal inductance regime lay in its being able to create plasmas with fusion power equaling that of supershots with much less plasma current. Both configurations were thought to offer the promise of smaller, and therefore cheaper, fusion reactors than the conventional tokamak. The additional capability of being able to study both these plasma configurations in both D-D and D-T widened the experimental range. The relevance to fusion power studies was enhanced by the strong RF heating capability in TFTR.

There was little new diagnostic construction this year except for those efforts in preparation for operation next year (see FY1997 below). Measurements of the behavior of alpha particles provided a major scientific contribution. The energy spectrum of the confined alpha particles and data on their losses were obtained for all the plasma scenarios. By careful tailoring of the plasma conditions, a great deal was learned about the interactions of the fast alpha particles with instabilities, both in causing the instabilities and being affected by them. The close agreement between observation and theoretical projection of the TAE instability was most satisfying.



The spatial profile of the fusion power density of two TFTR plasmas compared to the fusion power density projected for ITER (95GR150).

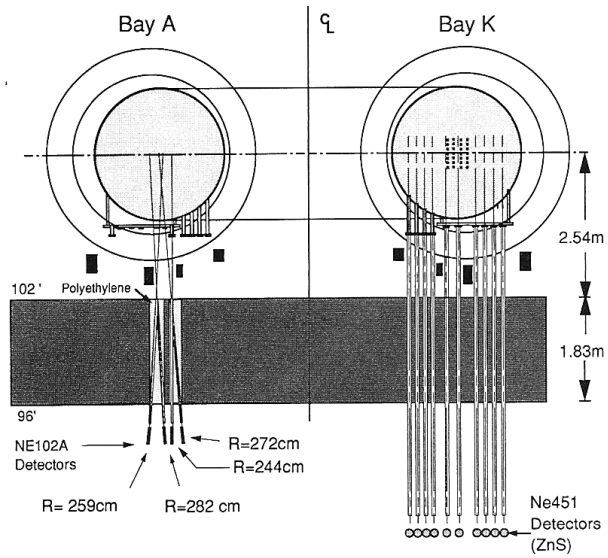
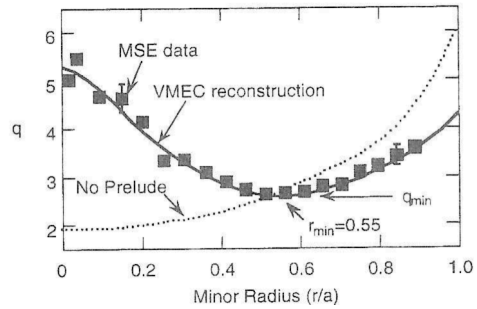


Diagram showing the addition of four new lines of sight for the neutron collimator (Bay A on the left) to provide good spatial resolution at the center of the plasma (Roquemore et al., RSI, **68**, 544 (1997)).



The observed minimum in the safety factor q showing
the agreement between the data and a modeled reconstruction
(Levinton et al., IAEA Fus. Energy Conf., 1996 Vol. 1, 211).

Fiscal Year 1997

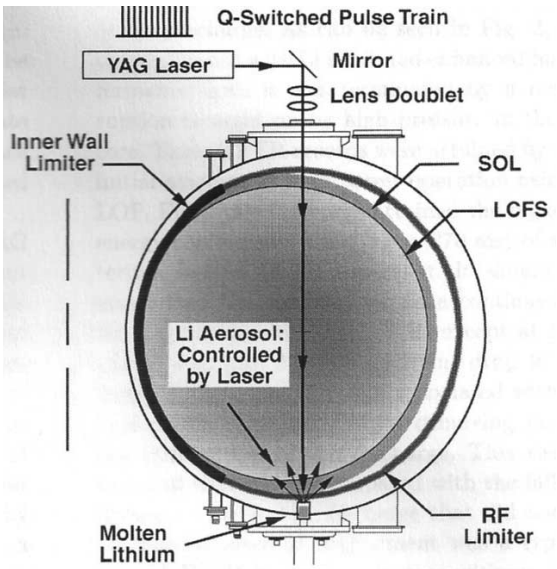
DOE's decision brought operation of TFTR to an end on April 4th. TFTR had clearly demonstrated that high quality experimental work could be carried out safely with tritium in tokamaks. It provided a huge amount of information, both technological and scientific. It also left a number of unanswered questions about confinement at high-β and its dependence on mass, which are still open in 2015. Unfortunately, the budget reductions and the need for funds to be used in decommissioning TFTR meant that staff had to be reduced again. This time the reductions in the personnel working on diagnostics at PPPL were devastating.

Three new ICRF antennae were installed for use in the final operational run. The main physics effort in the three months of experiments was devoted to the study of transport barriers and flow shear in the plasma. The new diagnostics showed large velocity shear with the transition to the ERS mode, and a concurrent high radial electric field. Experiments on different modes of heating of the core plasma with ICRF showed promise but unfortunately could not be concluded. The DOLLOP system (see below) resulted in improvement in the supershot plasma performance.

The ability of only four lithium pellets injected on each shot to inhibit gas emerging from the wall seemed to limit the potential of lithium coating for improving plasma performance. So an alternative "aerosol" technique was installed at the end of the last year and played an important role in the remaining experiments. This tastefully named system, DOLLOP (deposition of lithium by laser outside the plasma), consisted of a Q-switched YAG laser firing pulses of 8 ns width continuously for up to 2 s through a window on top of the tokamak onto a lithium cauldron on the bottom of the vacuum vessel to produce a lithium aerosol to coat the limiter. The improvements in plasma performance were immediately obvious.

Two significant new diagnostic capabilities were added. The need for a measurement of plasma poloidal rotation led to the difficult addition of opposing top and bottom views of the plasma by a CHERS system by Ron Bell. The complexity was necessary to take account of atomic physics effects. The second new capability was a significant upgrade of the MSE system with new fibers and detector channels to allow

detection of the line emission from the half-energy component of one of the neutral beams to permit measurement of the poloidal magnetic field and the radial electric field in the plasma.



Schematic of the DOLLOP lithium aerosol injector (Mansfield et al., Nucl. Fus., **41**, 1823 (2001)).

Scene in the control room very early on April 4, 1997 at the end of TFTR's extraordinary scientific program.

Some Diagnostics never made it to TFTR

Not all diagnostic ideas for TFTR reached fulfillment on the tokamak. It was thought that a direct measurement of the radial electric field in the plasma was essential, so development of a heavy-ion beam probe was started. Because of the high magnetic field in TFTR, it was necessary to have very heavy ions and Joe Cecchi worked to develop a beam for gold. However the test of the beam on PLT proved very disappointing. In addition, the arrangement that would have been required on TFTR was extremely complex and space-absorbing. Hence the technique was shelved.

Doug Post was an early pioneer in thinking about measuring the alpha particles. He considered the use of a neutral helium beam whose atoms would exchange charge with the alpha particles, allowing them to either emit light (singly-charged) or escape across the magnetic field (neutralized) and be analyzed. Bick Hooper (LBNL) and Larry Grisham showed that one could get a sufficient current with a He^0 beam. But issues with the metastable neutral He beam making quantitative measurement problematic led to consideration of a Li beam. Then it was shown that calibration of a ~6 MeV, 100 mA Li^6 beam would not be possible, so the idea was abandoned.

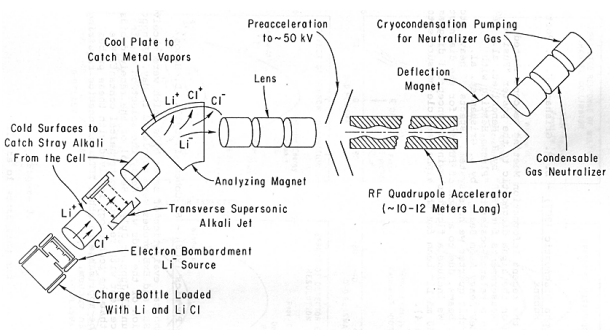
It was hoped that one could use a high power CO_2 laser for use in collective scattering for measuring the ion temperature and then potentially the alpha particles. Larry Johnson and T.K. Chu did develop such a

laser and its technology was used in powering the far-infrared interferometer, but the laser was not applied directly on TFTR.

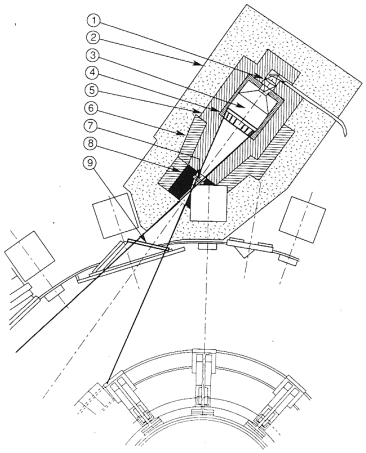
A near-UV Czerny-Turner spectrometer, FLOPSY[2], which could rapidly scan the plasma vertically in 10 ms, every 25 ms, with a rotating mirror prism was proposed to enable locating the sources of impurity spectral lines. Although developed, this instrument was never installed because of the better capability of the vertical-viewing CHERS instruments.

In 1989 it was decided to design and build a tangential-viewing x-ray imaging system to enhance the measurements of long-wavelength MHD activity and follow plasma motion better. When shielding this system sufficiently proved almost impossible for D-T in TFTR, Schwick von Goeler took it to PBX-M, where it contributed to the understanding of the lower hybrid current drive.

An injector of ferrocene, an iron-incorporating gas, was developed by Hulbert Hsuan in 1993 to provide iron in the plasma core to enhance the signal strength for the x-ray crystal spectrometer. While it would have been better for this purpose than the laser impurity injector, and it was successfully demonstrated in the laboratory, it was not installed.



Schematic diagram of the proposed lithium beam for an α-particle diagnostic (TFTR 38 (1981)).



Plan view of the tangential hard x-ray imaging system on PBX-M. It was not possible to provide sufficient shielding when designed for TFTR (Kaita et al., RSI, **61**, 2756 (1990)).

A Very Short Summary

Table 2 shows some measures of the achievement in improved plasma parameters on TFTR between its conception and its closure. Perhaps the best way to summarize the progress in diagnostic measurements made on TFTR is to record in a table the significant advances for plasma measurement that were made, shown with the relevant reference in Appendix 3. But beyond this list other measurements were made with better spatial and temporal resolution than was available for other devices. Unfortunately, the premature closure of the TFTR program meant that none of the alpha particle diagnostics ever achieved their full capability, which would have been of great value for ITER.

Table 2: Extrapolation of TokamakParameters

	1974	TFTR	Increase
Plasma Current (MA)	0.3	3	~10
Toroidal Field (T)	2	5.2	~1
Magnetic Energy (GJ)	0.01	1.5	$\sim 10^2$
Auxiliary Heating (MW)	0.2	30	$\sim 10^2$
FuelD	D-T	< 2	
T_i (keV)	1	10	~10
Pulse Length (s)	0.01	10	$\sim 10^3$
nTt (10^{20} m^{-3}keVs)	0.01	10	$\sim 10^3$
Fusion Power (MW)	0.0000001	10	$\sim 10^8$
Fusion Power Gain	0.0000003	~1	$\sim 3 \times 10^6$

Meade SOFE 1997 IEEE

Acknowledgements

Most of the key supporters of the efforts on TFTR Diagnostics have been acknowledged earlier in the text. But a huge debt is due to the other members of the staff of PPPL. The technician staff of the Diagnostics Division provided incredible creative work. The measurement successes could not have been achieved without the staff of the TFTR Operations Division under, at different times, Jim Sinnis, Rich Hawryluk and Joel Hosea; the Physics group under Dale Meade, Rob Goldston and Kevin McGuire, or the Computer Division under Ned Sauthoff and Dori Barnes. Key support in the Engineering Department, led by Jack Joyce, was provided for vacuum systems (Dave Mullaney), cleaning components for going under vacuum (Tom Provost), electronic instrumentation (Tom O'Connor, Charlie Staloff, Myron Norris and John Lowrance), and mechanical design. Also without the timely efforts by people in the manufacturing shops, and in the Procurement, Safety and Human Resources departments, life would have been much more problematic, if not impossible

I, personally, owe my deepest gratitude to my wife and children who somehow tolerated my behavior. I suspect a great deal is owed by everyone involved in TFTR Diagnostics to their spouses and families who made significant sacrifices for our exciting experiences.

The key resource for this short history is the set of PPPL annual reports from FY 1982 to FY 1997 edited by Carol Phillips. The other important resource has been the biannual special issues of the "Review of Scientific Instruments" recording the Proceedings of the High Temperature Plasma Diagnostics meetings. I owe a lot to Michael Bell for his critical reading of an early draft of this history and to John Greenwald for his editing of the final draft.

All of the work described here was funded by the Department of Energy.

Appendix 1: TFTR Diagnostics Personnel

All the PPPL-employee co-authors of papers published about the diagnostics are listed in the table below.

H.G. Adler	P.C. Efthimion	F. Jones	R.W. Motley	S. Sesnic
H.M. Anderson	R.A. Ellis III	D.W. Johnson	D. Mueller	A. Smith
N.D. Arnold	W. Ernst	G. Johnson	D. Mullaney	F. Spinos
V. Arunasalam	G. Estepp	L.C. Johnson	T. Munsat	L.D. Stewart
G. Ascione	J. Faunce	W. Journey	H. Murphy	D.P. Stotler
W.M. Ayers	J. Felt	R. Kaita	T.J. Murphy	J.D. Strachan
T.W. Barcelo	V.S. Foote	D. Kaufman	A. Nagy	B.C. Stratton
J. Bartolick	E. Fredd	R.J. Knize	R. Nazikian	S. Suckewer
M.G. Bell	E. Fredrickson	T.A. Kozub	M. Norris	C. Sule
R.E. Bell	G. Gammel	R.B. Krawchuk	T. O'Connor	E.J. Synakowski
W. Bergin	T. Gibney	L.P. Ku	D.K. Owens	G.D. Tait
M. Bitter	S. Goldfarb	H.W. Kugel	R.W. Palladino	H. Takahashi
W.R. Blanchard	M.A. Goldman	G. Kuo-Petravic	H.K. Park	G. Taylor
R.L. Boivin	J.L. Goldstein	L. Lagin	R.F. Parsells	F. Tenney
F.P. Boody	R.J. Goldston	P.H. LaMarche	S.F. Paul	T. Terpstra
N.L. Bretz	N.N.Gorelenkov	J.Lehner	D.E. Post	E. Thomas
A. Brizard	J. Gorman	S.L. Liew	T. Provost	M.E. Thompson
R.V. Budny	G.J. Greene	P. Liu	S. Raftopoulos	W. Tighe
M. Capone	B. Grek	V. Locasale	A.T. Ramsey	J. R. Timberlake
S. Cauffman	L.R. Grisham	D. Loesser	W.A. Rauch	E. Tolnas
A. Cavallo	J. Gulizio	D. Long	M. Reale	H.H. Towner
J. Cecchi	G.W. Hammett	J.L. Lowrance	M.H. Redi	F.Y. Tsang
R.C. Chouinard	R.J. Hawryluk	R. Majeski	G. Renda	M. Ulrickson
T.K. Chu	S. Hayes	D.M. Manos	R.S. Ritter	S. von Goeler
S.A. Cohen	H.W. Hendel	D.K. Mansfield	J. Roberts	R. Waszazak
J. Coonrod	H.W. Herrmann	R.J. Marsala	J. Robinson	S. Weicher
R.C. Cutler	K.W. Hill	V. Mastrocola	P. Roney	J.C. Weisheit
D. Cylinder	W.J. Hojsak	E. Mazzucato	A.L Roquemore	R.M. Wieland
D.S. Darrow	R.B. Howell	M.P. McCarthy	S. Rossnagel	J.R. Wilson
W. Davis	H. Hsuan	J. S. McCauley	N.R. Sauthoff	A.W. Wouters
T. Deverell	A.G.A. Huibers	D. McCune	N. Schechtman	M. Yamada
W. Dieckman	R.A. Hulse	M. McGowan	G. Schilling	N. Young
M.D. Diesso	K. Ida	K.M. McGuire	J. Schivell	K.M. Young
D.L. Dimock	J.A. Isaacson	D. McNeill	G Schmidt	M.C. Zarnstorff
J. Dong	K.P. Jaehnig	M. McSmith	J.D. Schwarzmann	S.J. Zweben
L. Dudek	A. Janos	S.S. Medley	R. Shoemaker	
H.H. Duong	D.L. Jassby	D.R. Mikkelsen	S.D. Scott	
H.F. Dylla	F.C. Jobes	E. Moshey	S. Seiler	

Appendix 2: Collaborators on TFTR Diagnostics

In all more than 100 physicists from outside Institutions contributed to the TFTR diagnostic successes. All contributing co-authors of Diagnostic papers are shown in the table below.

R.E. Aamodt	Lodestar Research Corp.
M.A. Abdou	UCLA
E.A. Azizov	TRINITI, Troitsk, Russia
C.W. Barnes	Los Alamos National Lab.
R. Batasz,	Sandia Nat. Lab., Livermore CA.
S.H. Batha	Fusion Physics & Technology
T.S. Bigelow	Oak Ridge National Lab.
H. Bindslev	JET Joint Undertaking, U.K.
H.-S.Bosch	Max-Planck, Garching, Germany
D.A. Boyd	U. Maryland
R. Büchse	Max-Plank, Garching, Germany
C.E. Bush	Oak Ridge National Lab.
F.E. Cecil	Colorado School of Mines
Z.Y. Chang	U. Wisconsin
P.Y. Cheung	Lodestar Research Corp.
C.P. Chong	U. Toronto, Toronto, Canada
R.E. Chrien	Los Alamos National Lab.
B.J. Clifton	MIT
R.J. Colchin	Oak Ridge National Lab.
I. Collazo	Oak Ridge National Lab.
G. Cosby	U. Wisconsin
J. Doane	General Atomics
H.H. Duong	General Atomics
R.D. Durst	U. Wisconsin
T. Elevant	RTI, Stockholm, Sweden
A.C. England	Oak Ridge National Lab.
H. T Evensen	U. Wisconsin
M. Finkenthal	Hebrew U., Jerusalem, Israel.
C.L. Fiore	MIT
R.K. Fisher	General Atomics
R.J. Fonck	U. Wisconsin (after PPPL)
M.E. Frey	MF Physics
J. Fujita	NIFS, Nagoya, Japan
D. Garnier	MIT
J. Gilmore	MIT
D.L. Griscom	Naval Research Laboratory
G.R. Hanson	Oak Ridge National Lab.
W.W. Heidbrink	University of California, Irvine
D.L. Hillis	Oak Ridge National Lab.
D.P. Hutchinson	Oak Ridge National Lab.
S. Itoh	Nagoya University, Japan
R.J. Jordan	EG&G Energy, Las Vegas
Y.J. Kim	U. Wisconsin
V.S. Khrunov	Phys. & Tech., Dubna, Russia
A.V. Khudoleev	Ioffe Inst., St. Petersburg, Russia
J. Kiraly	Inst. Isotopes, Budapest, Hungary
J. Kodaira	NIFS, Nagoya, Japan
A.V. Krasilnikov	TRINITI, Troitsk, Russia
A. Kritz	City College of New York
A. Kumar	UCLA
A.R. Larson	Los Alamos National Lab.
M.J. Lavelle	EG&G Energy, Las Vegas
F.M. Levinton	Jaycor, Fusion Phys. & Tech.
M.J. Loughlin	JET Joint Undertaking, U.K.
N.C. Luhmann, Jr.	UCLA
C.H. Ma	Oak Ridge National Lab.
R.G. Macauley-Newcombe	McMaster U., Hamilton, Canada
J.M. McChesney	General Atomics
J.S. Machuzak	MIT
R.J. Maqueda	Los Alamos National Lab.
E.S. Marmar	MIT
G.R. McKee	U. Wisconsin
C. Mayo	SAIC
P.D. Morgan	JET Joint Undertaking, U.K.
W. Morris	U. Oxford, U.K.
K.G. Moses	Jaycor
M. Murakami,	Oak Ridge National Lab.
E.B. Nieschmidt	Idaho National Engineering Lab.
T. Nishitani	JAERI, Japan
J. Norem	Argonne National Lab.
Y. Nagayama	University of Tsukuba, Japan
A. Ödblom	Chalmers. Gothenburg, Sweden
P.M. O'Gara	EG&G Energy, Las Vegas
M. Osakabe	Grad. U., Nagoya, Japan.
V. Paré	Oak Ridge National Lab.
P.B. Parks	General Atomics
M.P. Petrov	Ioffe Inst., St. Petersburg, Russia
C.S. Pitcher	U. Toronto, Toronto, Canada
W. Primak	Argonne National Lab.
D.A. Rasmussen	Oak Ridge National Lab.
E. Ruskov	University of California, Irvine
D.A. Russell	Lodestar Research Corp.
W.C. Sailor	Los Alamos National Lab.
T. Saito	JAERI, Japan
V. Sannikov	Kurchatov Institute, Russia.
M. Sasao	NIFS, Nagoya, Japan
R. Scarberry	Los Alamos National Laboratory
J.L. Schwob	Hebrew U., Jerusalem, Israel
V.Yu. Sergeev	Tech. U., St. Petersburg, Russia
J.E. Simpkins	Oak Ridge National Lab.
J.A. Snipes	Massachusetts Institute of Technology
P.C Stangeby	University of Toronto, Toronto, Canada
F.J. Stauffer	U. Maryland
L.D. Stewart	Exxon Nuclear Co.
M. Tavernier	Institut Curie, Paris, France
J.L. Terry	Massachusetts Institute of Technology
T.A. Thorson	U. Wisconsin
F.Y. Tsang	Idaho National Engineering Lab.
H.Y.W. Tsui	University of Texas
S.L. Turner	SAIC
M. Tuszewski	Los Alamos National Lab.
K.L. Vander Sluis	Oak Ridge National Lab.
W.R. Wampler	Sandia Nat. Lab., Albuquerque, N.M.
J.B. Wilgen	Oak Ridge National Lab.
F. Wising	Chalmers Univ., Gothenburg, Sweden
A.J. Wootton	University of Texas
P.P. Woskov	Massachusetts Institute of Technology
G. A. Wurden	Los Alamos National Lab.
M. Yamanishi	NIFS, Nagoya, Japan
G. Zigler	SAIC

Appendix 3: Some Innovative Aspects of Plasma Diagnostics on TFTR

1. Radiation-hard platinum grid bolometers[1].
2. Fast-scanning Michelson interferometer for ECE measurement[2].
3. Neutral particle measurement with E//B analzers[3].
4. Measurement of neutron fluxes over huge dynamic range (epithermal detectors)[4].
5. Measurement of neutron (and alpha-particle) source profiles by a neutron collimator[5].
6. In-vessel illumination for inspection[6].
7. Fusion gamma measurement[7].
8. Measurement of the species mix of a neutral beam[8].
9. Measurement of full density profile by far-infra-red interferometry[9].
10. Installed neutral beam for diagnostic purposes only[10].
11. Measurement of metallic ion transport by charge exchange recombination spectroscopy[11].
12. Measurement of profiles of ion temperature and toroidal rotation by X-ray spectroscopy[12].
13. Density fluctuation measurement by X-mode microwave scattering[13].
14. Radiation shielding developed for diagnostics in exposed locations[14].
15. Measurement of density fluctuations by beam emission spectroscopy (BES)[15].
16. Measurement of radio-frequency emission by probes[16].
17. Measurement of escaping fusion tritons by collector probes[17].
18. Observation of reconnection in a sawtooth crash.
19. Measurement of current density profiles (q(r)) in single shot[19].
20. Remotely-controlled radiation-hard optical imaging system[20].
21. Mechanized switching of fiber-optics[21].
22. Simultaneous measurement of DD and DT neutrons by He-4 proportional counters[22].
23. Remote operation of diagnostics from home, office desk or elsewhere[23].
24. Measurement and theoretical interpretation of correlation reflectometry[24].
25. Measurement of locked magnetic modes[25].
26. Use of an accelerator-based neutron source for in-vessel calibration[26].
27. Measurement of escaping alpha particles by scintillator probes[27].
28. Measurement of slowing-down confined alpha particles by charge exchange spectroscopy (CHERS)[28].
29. Measurement of confined alpha particles by pellet charge exchange (PCX)[29].
30. Measurement of and amelioration schemes for radiation effects on fiberoptics[30].
31. Measurement of behavior of light emitted by impurity pellets[31].
32. Measurement of neutron fluence by use of activation foils ("rabbit system")[32].
33. Measurement of helium ash[33].
34. Neutron measurements with a scintillating fiber[34].
35. Correlation of long-wavelength fluctuations by grating polychromator[35].
36. Microwave reflectometry for edge density measurement[36].
37. Measurement of tritium recycling by Fabry-Perot spectroscopy[37].
38. Use of foil deposition for measuring escaping alpha–particles[38].
39. Establishing cross-correlation for many types of neutron detectors[39].
40. Optical measurement of high-frequency ion temperature turbulence[40].

41. Measurement of spatial distribution of neutron fluctuation sources[41].
42. Poloidal rotation profile measurement with opposing sightlines[42].
43. Neutron spectroscopy using diamond detectors[43].
44. Operation of optical fibers hot to ameliorate radiation effects[44].
45. Lithium conditioning (DOLLOP)[45].

References

1. J. Schivell et al., *Rev. Sci . Instrum.*, **53**, 1527 (1982).
2. F.J. Stauffer et al., *Rev. Sci . Instrum.*, **56**, 925 (1985).
3. A.L. Roquemore et al., *Rev. Sci. Instrum.*, **56**, 1120 (1985).
4. E.B. Nieschmidt et al., *Rev. Sci. Instrum*, **56**, 1084 (1985).
5. H.W. Hendel, *IEEE Trans. Nucl. Sci.*, **33**, 670 (1986).
6. S.S. Medley et al., *Rev. Sci. Instrum.,* **56**, 1873 (1985).
7. S. S. Medley et al., *Rev. Sci. Instrum,,* **56**, 975 (1985).
8. H.W. Kugel et al., *Rev. Sci. Instrum.*, **57**, 2066 (1986).
9. D.K. Mansfield et al., *Appl. Optics*, **26**, 4469 (1987).
10. G. Schilling et al., *Rev. Sci. Instrum.*, **57**, 2060 (1986)
11. R.J. Knize et al., *Rev. Sci . Instrum.*, **59**, 1518 (1988).
12. M. Bitter et al., *Rev. Sci . Instrum.*, **59**, 2131 (1988).
13. N.L. Bretz et al., *Rev. Sci . Instrum.*, **59**, 1538 (1988).
14. A.L. Roquemore et al., *Rev. Sci . Instrum.*, **59**, 1726 (1988).
15. R.J. Fonck et al., *Rev. Sci . Instrum.*, **61**, 3487 (1990).
16. G.J. Greene in *Proceedings of the 17th Int. Conf. on contr. Fus. and Plasma Heating,* **IVB**, 1540 (1990).
17. R. Bastasz et al., *Rev. Sci. Instrum.*, **61**, 3199 (1990).
18. Y. Nagayama et al., *Phys. Rev. Lett.*, 67, 3527 (1991).
19. F.M. Levinton et al., *Rev. Sci . Instrum.*, **63**, 5157 (1992).
20. S.S. Medley & L.C. Johnson, *Rev. Sci. Inst.*, **63**, 4738 (1992).
21. S.F. Paul et al., *Rev. Sci . Instrum.*, **63**, 4921 (1992).
22. J. S. McCauley & J. D. Strachan, *Rev. Sci. Instrum.*, **63**, 4536 (1992).
23. R.J. Fonck et al,. *Rev. Sci. Instrum.*, **63**, 4803 (1992).
24. E. Mazzucato and R. Nazikian, *Phys. Rev. Lett.*, **71**,1840 (1993).
25. H. Takahashi et al., *Rev. Sci. Instrum.*, **66**, 816 (1995) (Abstract only).
26. D.L. Jassby et al., *Rev. Sci. Instrum.*, **66**, 891 (1995).
27. S.J. Zweben et al., *Nuclear Fusion*, **35**, 893 (1995)
28. G. McKee, et al., *Phys. Rev. Lett.*, **66**, 649 (1995).
29. R.K. Fisher et al., *Phys. Rev. Lett.*, **66**, 846 (1995).
30. A.T. Ramsey et al., *Rev. Sci . Instrum.*, **66**, 871 (1995).
31. D.K. Mansfield et al., *Rev. Sci . Instrum.*, **66**, 841 (1995) (Abstract only).
32. C.W. Barnes et al., *Rev. Sci . Instrum.*, **66**, 888 (1995).
33. E.J. Synakowski et al, *Phys. Rev. Lett.*, 75, 3689 (1995).
34. G.A. Wurden, et al., *Rev. Sci. Instrum*, **66**, 901 (1995).
35. A. Janos et al., Rev. Sci. Instrum., **66**, 668 (1995).
36. J.B. Wilgen, et al., Rev. Sci. Instrum., **66**, 863 (1995).
37. C.H. Skinner, et al., *Rev. Sci. Instrum.*, **66**, 646 (1995).
38. H.S. Herrmann et al., *Rev. Sci. Instrum.*, **66**, 351 (1995).
39. L.C. Johnson et al., *Rev. Sci. Instrum.*, **66**, 894 (1995).
40. H.T. Evenson et al., *Rev. Sci. Instrum.*, **66**, 845 (1995).
41. S. von Goeler et al., *Rev. Sci. Instrum.*, **67**, 473 (1996).
42. R.E. Bell, *Rev. Sci . Instrum.*, **68**, 1273 (1997).
43. A.V. Krasilnikov et al., *Rev. Sci. Instrum*, **68**, 553 (1997).
44. A.T. Ramsey et al., *Rev. Sci. Instrum*, **68**, 4735 (1997).
45. D.K. Mansfield et al, *Nucl. Fus.*, **41**, 1823 (2001).

Princeton Plasma Physics Laboratory
Office of Reports and Publications

Managed by
Princeton University

under contract with the
U.S. Department of Energy
(DE-AC02-09CH11466)

P.O. Box 451, Princeton, NJ 08543
Phone: 609-243-2245
Fax: 609-243-2751

E-mail: publications@pppl.gov

Website: http://www.pppl.gov